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LOUIS N. RIDENOUR, *Editor-in-Chief*

COMPONENTS HANDBOOK

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Edited by

JOHN F. BLACKBURN

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COMPONENTS HANDBOOK

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Foreword

THE tremendous research and development effort that went into the development of radar and related techniques during World War II resulted not only in hundreds of radar sets for military (and some for possible peacetime) use but also in a great body of information and new techniques in the electronics and high-frequency fields. Because this basic material may be of great value to science and engineering, it seemed most important to publish it as soon as security permitted.

The Radiation Laboratory of MIT, which operated under the supervision of the National Defense Research Committee, undertook the great task of preparing these volumes. The work described herein, however, is the collective result of work done at many laboratories, Army, Navy, university, and industrial, both in this country and in England, Canada, and other Dominions.

The Radiation Laboratory, once its proposals were approved and finances provided by the Office of Scientific Research and Development, chose Louis N. Ridenour as Editor-in-Chief to lead and direct the entire project. An editorial staff was then selected of those best qualified for this type of task. Finally the authors for the various volumes or chapters or sections were chosen from among those experts who were intimately familiar with the various fields, and who were able and willing to write the summaries of them. This entire staff agreed to remain at work at MIT for six months or more after the work of the Radiation Laboratory was complete. These volumes stand as a monument to this group.

These volumes serve as a memorial to the unnamed hundreds and thousands of other scientists, engineers, and others who actually carried on the research, development, and engineering work the results of which are herein described. There were so many involved in this work and they worked so closely together even though often in widely separated laboratories that it is impossible to name or even to know those who contributed to a particular idea or development. Only certain ones who wrote reports or articles have even been mentioned. But to all those who contributed in any way to this great cooperative development enterprise, both in this country and in England, these volumes are dedicated.

L. A. DuBRIDGE.

Preface

THIS volume is intended primarily as a companion and reference work for Vols. 18 through 23 of the Radiation Laboratory Series. It contains data on a number of classes of electrical and electronic components which are of principal interest to the designer of receiving and test equipment. In so far as possible it emphasizes the components which were developed by or under the sponsorship of the Radiation Laboratory, or were of primary importance in its work. In order to avoid a one-sided presentation, however, this material has been supplemented with other data so that in most cases an individual chapter approximates a survey of current practice in its particular field.

The title "Components Handbook" is undoubtedly too inclusive for the volume as published, since the circumstances under which it was written have unfortunately prevented the inclusion of chapters on several important classes of components and have also had some effect on the contents of those that were included. The most serious omission is probably that of fixed condensers. Chapters were also projected on air-core inductors, on mechanical components, and on several other subjects. Credit is due the authors who contributed to these chapters; the omission of their work was due neither to any faults of the work itself nor to a lack of interest in the subject matter, but solely to the fact that the termination of the Office of Publications caused these chapters to be left out. Their omission is a serious if unavoidable defect.

The completeness of coverage of a particular field depends in large measure upon the amount of time which the individual author was able to devote to it. The necessity for the immediate acceptance of postwar jobs, usually far from Cambridge, made it impossible for most of the authors to check their work in final manuscript form. In such cases the editor hopes that the collation and condensation of the original drafts have not resulted in serious errors of fact or in undue distortion of the presentation.

In order to make the volume useful both to the academic research worker and to the engineer in the industrial laboratory the editor has tried in most cases to combine the generalized "survey-of-a-field" form

with a reasonable amount of specific data, largely in tabular form. For discussions of the accuracy and balance of several of the chapters indebtedness is expressed to their authors or to others equally familiar with the subjects. These discussions have considerably improved the book.

It is a pleasant task to record appreciation of the help of the many people, both in the Office of Publications of the Radiation Laboratory and outside, who have had a hand in the preparation of this volume. The lack of space prevents the listing of names, but this omission has been rectified as far as possible by the inclusion of credit lines to sources outside the Laboratory and by the following list of sources of the individual sections.

In a book such as this one it is difficult to apportion credit fairly because many of the chapters are the result of a process of synthesis and rearrangement that left little of the original reactants. The names listed at the heads of the chapters are those of authors who are responsible for major portions of those chapters; a somewhat more detailed list of credits follows: O. Abbiati, Secs. 12·9 through 12·11; F. N. Barry, Chap. 14; P. F. Brown, Secs. 5·1 and 5·2; F. E. Dole, Chap. 8; G. Ehrenfried, Chap. 2 and Secs. 3·14, 3·15 and parts of Secs. 3·9 and 3·10; M. D. Fagen, Secs. 1·1 through 1·11, 3·1 through 3·8, and part of Sec. 3·11; S. Frankel, Secs. 5·3 through 5·5; S. N. Golembe, parts of all sections of Chap. 4; W. F. Goodell, Jr., Secs. 10·1 through 10·16; E. A. Holmes, III, Chap. 9; M. M. Hubbard, Secs. 12·5, 12·6, 12·8, and 12·12; M. M. Hubbard and P. C. Jacobs, Jr., Secs. 12·3, 12·4, and 12·7; H. B. Huntington, Chap. 7; H. E. Kallman, Sec. 1·12 and Chap. 6; T. B. Morse, Chap. 11.

The volume editor is responsible for the remainder of the book and for numerous interpolations in the texts of some of the authors above. For advice and for miscellaneous data in connection with these interpolations, credit is due to a number of members of the Radiation Laboratory, including the following: H. F. Brockschmidt and D. N. Summerfield, for data on engine-driven generator sets in Secs. 12·3, 12·4, and 12·5; C. E. Foster, for reviewing Chaps. 10 and 13 and for additional data for these chapters; C. E. Foster and E. R. Perkins, for original rough draft of Chap. 10; M. M. Hubbard, for reviewing Chaps. 4, 11, and 12; J. M. McBean, for data on the electronic line-voltage stabilizer of Sec. 12·13; R. J. Sullivan, for reviewing Chap. 8, and for additional data; C. A. Washburn, for data on high-voltage power-supply transformers of Sec. 4·3, and for data on M-1060 regulator tube in Sec. 14·2.

It may seem invidious to single out an individual for credit when so many have helped, but the editor cannot refrain from expressing gratitude to Mr. F. N. Barry, who performed the laborious task of compiling the tables of receiving tubes and who wrote the accompanying text for Chap. 14. Most of this work was done after his termination from the

Laboratory and his acceptance of another job, and at considerable personal sacrifice.

The editor is also deeply indebted to Mrs. Barbara D. Coté for her faithful and efficient services as editorial and production assistant, and to his wife, Harriet, for aid in typing and proofreading.

The publishers have agreed that ten years after the date on which each volume in this series is issued, the copyright thereon shall be relinquished, and the work shall become part of the public domain.

JOHN F. BLACKBURN.

CAMBRIDGE, MASS.,
October, 1947.

Contents

CHAPTER 1

WIRES AND CABLES

BY M. D. FAGEN AND H. E. KALLMANN

This chapter will be concerned only with two main classes of conductors for which joint Army-Navy (JAN) Specifications have been issued. These include the types of insulated wire ordinarily used in internal chassis wiring and in interconnections between chassis where the frequency, voltage, and power levels permit, hereafter referred to as wires, and the recently developed low-loss flexible coaxial cables generally used for the transmission of triggers, gates, i-f and video signals, and high-voltage modulator pulses. Data on magnet wire will be found in Chap. 4 and on resistance wire in Chap. 8 of this volume.

HOOK-UP WIRE

The class of wires used for hook-up and cabling purposes normally consists of a solid or stranded tinned copper conductor, in sizes AWG No. 24 to AWG No. 6, covered by a primary insulation of a natural rubber compound, a synthetic rubber like Butyl or Buna S, or one of the plastic elastomers like Vinylite or Polyethylene. Over this insulator is an outer covering of a textile braid made of cotton, fiber glass, nylon, or rayon. The primary insulation may be applied by extrusion, by dipping or spraying, or in the form of several layers of tape, subsequently amalgamated or cured to form a continuous tube adhering to the conductor. The outer covering is a closely woven braid, colored and often carrying a contrasting tracer for identification, and treated with multiple coatings of transparent flexible lacquer to impart a smooth finish. Each of the many possible combinations of primary insulations and outer coverings has characteristics and properties that suit it particularly for some special conditions of operation but there is no single type that meets every requirement. The properties of the various insulations commonly used and of the finished wires commercially obtainable will be discussed drawing freely from the limited amount of published information available,[1] and from pertinent joint Army-Navy Specifications[2] and Components Lists.[3]

[1] J. M. Caller, "Characteristics of Radio Wire and Cable," *Radio*, **28**, No. 5, 25–28, 58 (May 1944), and No. 6, 28–31, 64, 66 (June 1944); E. D. Youmans, "Plastic Insulation for Conductors," *Elec. World*, **CXX**, 457–459 (August 1943) and 812–815 (September 1943); *Tables of Dielectric Materials*, I and II, Laboratory for Insulation Research, Massachusetts Institute of Technology.

[2] Joint Army-Navy Specification JAN-C-76, Cable (Hook-up Wire), Electric, Insulated, Radio and Instrument, Aug. 19 1945.

[3] Standard Components List, Number 5. Available from Army-Navy Electronics Standards Agency, Red Bank, N. J.

A list of hook-up wires may be found in the Army-Navy Electronics Standards Agency Standard Components List as issued May 5, 1945 and July 20, 1945. These have been approved either by the Signal Corps under Specification 71-4943 or by the Army-Navy Electronics Standards Agency under Joint Specification JAN-C-76, wire type WL (general purpose applications, thermoplastic insulation for use at 600 volts rms or less.)

For convenience of reference, the JAN type designation is built up as follows:

1. letters representing the type of wire, as WL;
2. numbers giving the approximate cross section of the conductor in thousands of circular mils, as WL-1½ for 1500 circular mils;
3. a number in parentheses designating the minimum number of strands, as WL-1½ (1) for solid wire, or WL-1½ (7) for stranded wire made up of 7 strands;
4. numbers representing the AWG wire size, as WL-1½ (7) 18 for No. 18 stranded wire;
5. numbers representing the color code, as WL-1½ (7) 18-96 for white wire with a blue tracer.

1·1. The Conductor.—The conductor used in hook-up wire is soft annealed round copper, stranded or solid, and almost always tinned. The reasons for the choice of copper are well recognized: low cost, good conductivity, low temperature coefficient, high ductility, and good resistance to corrosion and fatigue. Stranded wire is almost invariably used for hook-up and interconnection purposes because of its greater flexibility under the shock and vibration conditions present in mobile installations of electronic equipment. There is a strong feeling, based on some evidence, that solid conductors used for hook-up purposes in sizes smaller than AWG No. 22 may "crystallize" under sustained vibration such as is encountered, for example, in aircraft service. Recommendations for such applications are that stranded wire be used wherever practicable, and solid wire be limited to jumper connections or to r-f circuits where the conductor may be rigidly held in place to limit its motion. Other reasons for the choice of stranded wire are the following:

1. A slight nick on the surface of a solid conductor, such as might occur during the removal of insulation, can easily become a point at which, upon subsequent flexing of the wire, breakage will occur.
2. Stranded wire can easily be bent and formed into a neat wiring harness for chassis assembly.
3. Unsoldering and resoldering of a stranded-wire connection are less

likely to cause breakage of the wire due to the bending and twisting usually imposed in the operation.

Mechanical and Electrical Properties.—After it has been drawn, annealed, and tin coated, the copper wire should have tensile strength and elongation limits as given in Table 1·1.

Table 1·1.—Tensile Strength and Elongation Limits of Tinned Copper Wire

Diameter, in.	Tensile strength (maximum), lb per in.^{2}	Elongation, 10-in. test piece (minimum), %
0.003 to 0.011	40,000	10
0.012 to 0.020	39,000	15
0.021 to 0.102	38,500	20

Splices are permitted in the individual strands of a stranded conductor if they are of the butt-type, brazed with a silver-alloy solder. For wires in sizes No. 28 AWG and smaller, the splice may be twisted.

Table 1·2.—Stranded Hook-up Wire Data

AWG size	Standard copper strand sizes			Weight per ft of length, lb	Maximum resistance per 1000 ft at 25°C, ohms
	Nominal diameter, in.	Calculated diameter, in.	Area, Cir. mils		
40	0.0031	0.003145	10	0.0000299	1,240
39	0.0035	0.003531	13	0.0000377	985
38	0.0040	0.003965	16	0.0000476	780
37	0.0045	0.004453	20	0.0000600	620
36	0.0050	0.005000	25	0.0000757	490
34	0.0063	0.006305	40	0.000120	304
33	0.0071	0.00708	50	0.000152	239
32	0.0080	0.007950	63	0.0002413	188
31	0.0089	0.008928	80	0.0001913	149
30	0.0100	0.01003	101	0.000304	116
29	0.0113	0.01126	127	0.000382	92
28	0.0126	0.01264	160	0.000484	72
27	0.0142	0.01420	202	0.000610	57.5
26	0.0159	0.01594	254	0.000769	45.2
25	0.0179	0.01790	320	0.000969	35.8
24	0.0201	0.02010	404	0.00122	28.4
22	0.0254	0.02535	642	0.00194	17.7
20	0.0320	0.03196	1022	0.00309	11.1
19	0.0359	0.03589	1290	0.00390	8.78
18	0.0403	0.04030	1620	0.00492	6.94
17	0.0453	0.04526	2050	0.00620	5.49
16	0.0508	0.05082	2580	0.00782	4.34
15	0.0571	0.05707	3260	0.00986	3.44
14	0.0641	0.06408	4110	0.0124	2.73

Data on tinned copper wire as used in the manufacture of stranded hook-up wire are given in Table 1·2.

A stranded conductor is formed by twisting individual wires in one of the three following patterns.

1. Concentric stranding; one wire forms the central core and is surrounded by one or more layers of helically laid wires. The pitch of the outer layer of conductors is referred to as the lay of the stranding.
2. Bunch stranding; the required number of individual conductors are simply twisted together without regard to geometrical arrangement.
3. Rope stranding; groups of concentric stranded or bunched conductors are assembled in the same fashion as the individual conductors described under (1) above.

The concentric pattern is preferable because it yields a conductor essentially circular in cross section so that uniform wall thickness is obtained with extruded types of insulation. In addition, the individual wires do not separate when the insulation is stripped for soldering.

Some physical characteristics for tinned copper conductors as used in the manufacture of AN specification hook-up wire, solid and stranded, are given in Table 1·3.

TABLE 1·3.—PHYSICAL CHARACTERISTICS OF TINNED COPPER CONDUCTORS

Army-Navy size designation	AWG size	Minimum number strands	Maximum lay, in.	Nominal strand diameter (minimum stranding), in.	Diameter over conductor, in.	Nominal area, cir mils	Maximum resistance per 1000 ft at 25°C, ohms
$\frac{3}{8}$(1)	24	solid	.....	0.0201	0.020	404	28.4
$\frac{3}{8}$(7)	24	7	0.50	0.0080	0.025	442	28.4
$\frac{5}{8}$(1)	22	solid	.....	0.0254	0.025	642	18.01
$\frac{5}{8}$(7)	22	7	0.75	0.0100	0.031	642	19.0
1(1)	20	solid	.....	0.0320	0.032	1,022	11.33
1(7)	20	7	0.875	0.0126	0.039	1,020	11.93
$1\frac{1}{2}$(1)	18	solid	.....	0.0403	0.040	1,624	7.16
$1\frac{1}{2}$(7)	18	7	0.875	0.0159	0.049	1,624	7.52
$2\frac{1}{2}$(1)	16	solid	.....	0.0508	0.051	2,583	4.48
$2\frac{1}{2}$(19)	16	19	1.00	0.0113	0.060	2,407	4.73
4(1)	14	solid	.....	0.0641	0.064	4,107	2.82
4(19)	14	19	1.50	0.0142	0.072	3,828	3.13
6(19)	12	19	2.00	0.0179	0.090	6,088	1.92
9(37)	10	37	2.00	0.0159	0.109	9,402	1.27
17(133)	8	133	2.25	0.0113	0.169	16,824	0.732
27(133)	6	133	2.50	0.0142	0.213	26,800	0.454

1·2. The Primary Insulation.—There is a wide variety of insulating materials that may be used for coating solid and stranded tinned copper wire. The suitability of any particular type must be determined by careful examination of the electrical conditions of operation and the physical environment in which each operation is to take place. The electrical properties of the insulation will establish the dielectric strength, insulation resistance, loss factor, and dielectric constant. The physical properties will determine the upper and lower limits of operating temperature; resistance to moisture, flame, sunlight, oils, acids, alkalies, fungus, oxidation; effects of aging, abrasion, vibration, shock; flexibility, toughness, and mechanical strength. To some extent, these qualities will be controlled by the nature of the outer covering used over the primary insulation, a discussion of which will be given in Sec. 1·3.

The primary insulations most generally used are:

1. Thermoplastic Polymers.
   A. Vinyl Resins.
      a. Plasticized copolymers of vinyl chloride and vinyl acetate (Vinylite, Geon).
      b. Plasticized vinyl chloride polymers (Koroseal).
   B. Cellulose Derivatives.
      a. Cellulose acetate-butyrate compound, used in the form of tape applied over the conductor (Tenite II).
      b. Ethyl cellulose.
   C. Polyethylene (Polythene).
   D. Polyisobutylene (Polybutene, Vistanex).
2. Synthetic Rubbers.
   A. Butyl rubber, a copolymer of isobutylene and a small amount of butadiene or isoprene.
   B. Buna S, sometimes referred to as GR-S, a copolymer of butadiene and styrene.
3. Natural Rubber Compounds.

A general qualitative summary of some of the characteristics of these materials is given in Table 1·4. More detailed quantitative information on the electrical characteristics of the types of dielectrics commonly used may be obtained from the "Tables of Dielectric Materials" of the Laboratory for Insulation Research of M.I.T.[1]

An examination of these data indicates that the vinyl resins and cellulose derivatives have great utility for general-purpose hook-up wire. They have good dielectric strength and excellent moisture resistance, stability, and aging characteristics. They are noninflammable and

[1] Tables of Dielectric Materials, I and II. Laboratory for Insulation Research, M.I.T.

TABLE 1·4.—CHARACTERISTICS OF PRIMARY INSULATIONS

Name	Chemical type	Remarks	Type of use	Dielectric properties	Chem. properties	Resistance to ozone sunlight	Physical properties	Noninflammability	Oil resistance
Koroseal	Plasticized Vinyl chloride Polymer	Thermoplastic; extrudable; several types	Insulation or jacket	F	E	E	G	E	E
Vinylite	Plasticized Vinyl chloride-Vinyl acetate Copolymer	Ditto	Insulation or jacket	F	E	E	G	E	E
Neoprene	Chloroprene Polymer	Vulcanizable; rubber-like, extrudable or calendered strips; several types	Jacket	P	E	E	G	E	G
Buna S	Butadiene-Styrene Copolymer	Vulcanizable; rubber-like; extrudable	Insulation or jacket	G	G	F	G	P	F
Butyl Rubber	Isobutylene-Diolefin Copolymer	Ditto	Insulation	G	E	G	G	P	P
Thiokol	Organic Polysulfides	Both thermoplastic and vulcanizable types; extrudable	Jacket	P	G	E	F	P	E
Polybutene	Isobutylene Polymer	Not vulcanizable; rubber-like; mixed with resins or rubber; extrudable	Insulation	E	E	E	F	P	P
Polythene	Ethylene Polymer	Thermoplastic; extrudable	Insulation	E	E	E	E	P	F
Saran	Vinylidene chloride-Vinyl chloride Copolymer	Thermoplastic; applicable as threads or tapes	Insulation	F	E	E	G	E	E
Tenite II or Kodapak	Cellulose acetate-butyrate	Thermoplastic; extrudable or applicable as tapes	Insulation	F	G	G	G	F	G
Ethyl cellulose	Cellulose ethyl ether	Thermoplastic, extrudable	Insulation	F	G	G	G	F	G

NOTE: E, excellent.
G, good.
F, fair.
P, poor.

resistant to oils and most acids and alkalies. A limiting factor in their use is that like many other thermoplastics they soften at high temperatures and stiffen at very low temperatures, although the low limit has been extended to −50°C by recent improvements. Their relatively high dielectric constant and power factor make them undesirable for use at radio frequencies, where polyethylene is almost exclusively employed.

The synthetic rubbers, Butyl and Buna S, have dielectric properties somewhat better than the vinyl and cellulose materials but their resistance to solvents, particularly oils, is not as good. The natural-rubber compounds are little used at present for wire insulation. Technical developments during the years 1938 to 1945, intensified by war shortages of natural rubber, have resulted in large quantity production of thermoplastic polymers which are greatly superior to the rubber compounds which previously were standard, particularly with respect to the effects of heat, sunlight, weather, and oils.

1·3. The Outer Covering.—An outer covering is applied to act as a support for the primary insulation. It permits higher temperature of operation than would otherwise be possible, and also improves the abrasion resistance of the wire. The covering is one of two types: a closely woven braid of cotton, Fiberglas, nylon, or rayon; or an extruded jacket of nylon. The braid is colored for identification and coding, frequently carrying a tracer of contrasting color. If Fiberglas is used, a colored textile tracer provides the marking. The braid is treated with multiple coatings of transparent, flexible lacquer to make a smooth finish. It is necessary that the braid thus treated be noncorrosive, nontoxic, flexible, and resistant to moisture, flame, and fungus.

Lacquered cotton braid is superior to glass with respect to abrasion resistance, ease of color coding, and corona properties. Glass braid has the advantages of being inherently noninflammable and resistant to fungus, but some difficulty has been experienced with its tendency to fray at the point where insulation is stripped from the wire. This fraying, in addition to affecting the appearance of the wire, tends to transmit moisture by wicking action. For some purposes, it is of interest to examine the effect of the various coverings on the over-all diameter of the wire. Table 1·5 is a comparison of glass and cotton braid over acetate-butyrate tape and vinylite for stranded No. 22 and No. 14 wire. More complete data is given in Fig. 1·1. It is seen from Table 1·5 and Fig. 1·1 that cotton braid adds to the over-all diameter by an amount that might be significant in a wiring harness of 10 or 12 wires which is to be used in a crowded chassis.

Nylon and rayon are other possible choices for outer coverings. Nylon is applied in the form of an extruded coating approximately 0.005 in. in thickness. It has excellent abrasion resistance and wires

have been made with it which pass all the JAN specifications for flame and solvent resistance, cold bend, and insulation resistance. Rayon braids, in general, do not have abrasion resistance equal to cotton or nylon and are less widely used.

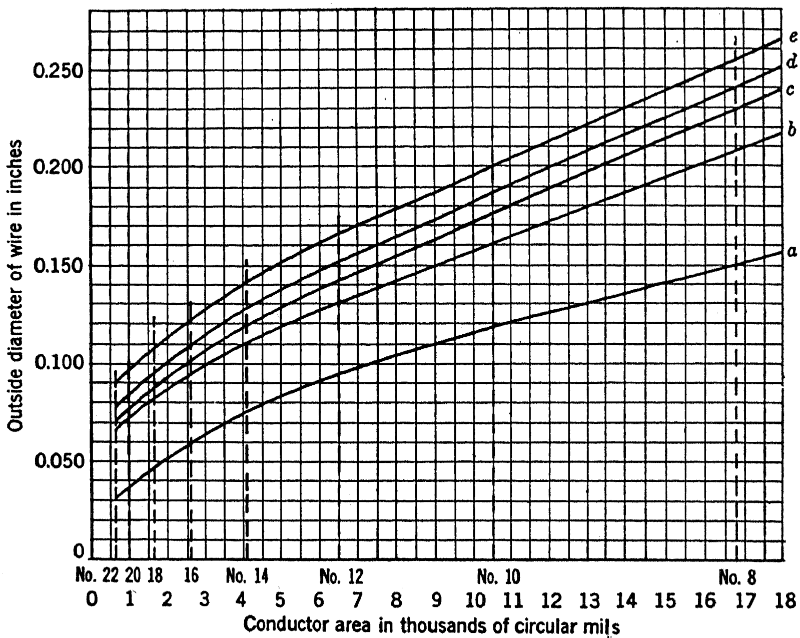


FIG. 1·1.—Outside diameters of radio hook-up wire: (*a*) bare stranded conductor; (*b*) butyrate-tape insulated, glass braided; (*c*) vinylite insulated; (*d*) vinylite insulated, glass braided; (*e*) vinylite insulated, cotton braided. (No. 30 AWG stranding of all wires for 750 volts continuous service.)

TABLE 1·5.—GLASS AND COTTON BRAID VS. ACETATE-BUTYRATE TAPE AND VINYLITE

Insulation	Over-all diameter, in.	
	No. 22 wire	No. 14 wire
Bare stranded conductor	0.03	0.075
Wire plus butyrate tape plus glass braid	0.068	0.110
Wire plus vinylite	0.071	0.119
Wire plus vinylite plus glass braid	0.079	0.128
Wire plus vinylite plus cotton braid	0.090	0.141

The maximum over-all diameter permitted for solid and stranded braid-covered or jacketed wires classified as type WL (general purpose applications, thermoplastic insulation, 600 volts rms or less) is given in Table 1·6.

TABLE 1·6.—MAXIMUM OVER-ALL DIAMETER PERMITTED FOR TYPE WL WIRE

Type (JAN-C-76)	Diameter over outer covering, in.	Type (JAN-C-76)	Diameter over outer covering, in.
WL-$\frac{2}{5}$(1)-24	0.080	WL-2$\frac{1}{2}$(1)-16	0.130
WL-$\frac{2}{5}$(7)-24	0.080	WL-2$\frac{1}{2}$(19)-16	0.130
WL-$\frac{3}{5}$(1)-22	0.090	WL-4(1)-14	0.150
WL-$\frac{3}{5}$(7)-22	0.090	WL-4(19)-14	0.150
WL-1(1)-20	0.100	WL-6(19)-12	0.170
WL-1(7)-20	0.100	WL-9(37)-10	0.200
WL-1$\frac{1}{2}$(1)-18	0.115	WL-17(133)-8	0.255
WL-1$\frac{1}{2}$(7)-18	0.115	WL-27(133)-6	0.310

Colors available for hook-up wire covering are limited to the following:

0 Black	5 Green
1 Brown	6 Blue
2 Red	7 Violet (purple)
3 Orange	8 Gray (slate)
4 Yellow	9 White

Two colors may be used: the first as the base color, the second as a contrasting tracer. The digit accompanying the color is used as part of the wire specification. For example, a white wire with a blue tracer has the number 96 as the final two numbers of its type designation.

1·4. Physical Properties of the Finished Wire. *High Temperature.*—To a large extent, the thermal properties of the finished wire determine its usefulness. At high temperatures, some insulations deteriorate rapidly, others soften and deform. At very low temperatures, they become brittle and may easily be damaged by flexing or vibration. The principles of maximum temperature rating for insulations are well formulated in one of the AIEE Standards.[1] They are briefly given here.

1. Insulation does not fail by immediate breakdown at a critical temperature, but by gradual mechanical deterioration with time. The question of what maximum temperature is safe can be answered only on the basis of how long the insulation is expected to last.
2. How long an insulation will last electrically depends not only on the class of insulation but also on the effectiveness of the physical support for the insulation.
3. Insulation life is dependent to a considerable extent on the access of oxygen, moisture, dirt, or chemicals.

[1] AIEE Standards No. 1. "General Principles Upon Which Temperature Limits are Based in The Rating of Electrical Machinery and Apparatus."

4. Physical deterioration of insulation, under the influence of time and temperature, increases rapidly with temperature.

Maximum temperature limits have been assigned in accordance with the above principles. For the types of insulation used in most hook-up wires, this is the Class A "hottest-spot" maximum of 105°C. Class A insulation consists of

1. Cotton, silk, paper, and similar organic materials when either impregnated or immersed in a liquid dielectric.
2. Molded or laminated materials with cellulose filler, phenolic resins, and other resins of similar properties.
3. Films and sheets of cellulose acetate and other cellulose derivatives of similar properties.
4. Varnishes (enamel) as applied to conductors.

In electronic apparatus, the limiting temperature may be reached not by temperature rise in the wire due to its own I^2R loss but solely by increase in temperature of the chassis interior due to vacuum-tube and resistor dissipation. It is not at all unusual to find a temperature rise of 40°C over ambient in a compact piece of equipment designed for airborne use. If the ambient temperature is 55°C, as is generally established in Army-Navy service specifications, a temperature of 95°C is attained apart from any rise contributed by the wire itself. If, in addition to this, filament or power conductors are considered it is evident that some thought must be given to the current-carrying capacity of insulated wires.

The AN high-temperature test calls for 24 hr of heating to 120°C, cooling to room temperature, tightly coiling the wire for five turns around a mandrel three times the outer diameter of the wire, immersing the coil in water for 1 hr, and finally applying a 60 cps test voltage. The general purpose wire (WL) must withstand 2000 volts rms for 1 min. High-voltage wire (SRHV) must withstand 6000 volts rms.

Low Temperature.—At very low temperatures the brittleness of the wire may impose serious limitations on its use, particularly in interconnecting cables where some flexing may be required or where vibration conditions are to be met. Present-day thermoplastic polymers as compounded for wire insulation should pass the following cold-bend test. The wire is cooled to -40°C, then tightly wrapped around a 1-in. mandrel (for wire sizes No. 24 to No. 16) for at least five turns, unwrapped and rewrapped in the opposite direction, immersed in tap water at room temperature and given a 60 cps voltage test as in the preceding paragraph.

Abrasion.—The abrasion resistance of insulated wire is important in determining how well it will stand up when used with other wires in

bound wiring harnesses or in flexible conduit to form interconnecting cables. The AN test describes a machine for stroking the wire with No. 3/0 120 sandpaper under specified conditions of length of travel, tautness of wire, rate, etc. General-purpose hook-up wire type WL must withstand a minimum of 200 strokes without exposing the conductor.

Solvents.—In mobile and industrial applications of electronic equipment there is always the possibility of contact with water, gasoline, motor oil, antifreeze solutions, alcohol, and in the case of marine equipment, salt water. Tests are prescribed for solvent resistance specifying immersion for 24 hr at room temperature, one sample in each of the liquids mentioned. At the end of this time the wire is wiped clean, immersed in water for 1 hr, and given the dielectric test described in the preceding paragraphs.

Flammability.—It is to be expected that at some time during the life of equipment, there will be failure of vacuum tubes or other components which may result in excessive current in some of the equipment wiring or in the components that may be close to a wiring harness. Inflammable insulation or protective lacquer may then become a dangerous fire hazard. The AN test specifies that the rate of burning be not more than 1 in./min after a Bunsen burner flame is applied for 30 sec to one end of a horizontal length of wire in a draft-free chamber and that burning particles shall not fall from the wire.

Fungus.—Under tropical conditions of high temperature and high humidity there is likely to be extensive failure of insulations because of moisture and fungus growth. The Signal Corps Ground Signal Agency has been energetically pursuing a program to improve the performance and reliability of equipment intended for tropical service by investigations of inherently resistant materials, and of fungicides suitable for surface treatment of components for incorporation into lacquer and varnishes. With regard to radio hook-up wires, three types of fungicide have been found suitable for incorporation into the saturants and lacquers used to impregnate the woven outer covering. These are 15 per cent salicylanilide,[1] 10 per cent pentachlorophenol,[2] and 1 per cent phenyl mercuric salicylate.

The AN specification requires a test in which the wire is exposed to a composite of four types of fungus organisms in a spore suspension for ten days at 95 per cent relative humidity and room temperature. At the end of this time there is to be no fungus growth on the wire covering.

Moisture.—The effect of sustained high moisture content in the atmosphere is particularly insidious in electronic equipment where, fundamentally, input impedances are high and electrical leakage must

[1] Du Pont Company "Shirlan Extra."

[2] Dow Chemical Co. "Dow No. 7"; Monsanto Chemical Co. "Santophen No. 20."

be kept to a minimum. This is particularly true when equipment is nonoperative for part of the time and where day-night air temperature cycles may result in condensation of vapor on the insulation. Hook-up wire should withstand 95 per cent relative humidity at 65°C for ten days, with temperature cycling to room temperature; 95 per cent relative humidity and −10°C for several hours of each 24-hr period. More complete information on a recommended humidity-temperature cycle for moisture resistance tests is contained in specification JAN-C-76. For general-purpose hook-up wire it is required that after exposure to the moisture test the insulation resistance between adjacent cabled wires should be at least 100 megohms, the dielectric strength should be at least 4000 volts rms (60 cps) and that between wrapped electrodes 1 in. apart on the surface of the wire, 2500 volts rms can be applied without flashover.

1·5. Electrical Properties of the Finished Wire.—The electrical properties of wire cannot be completely separated from its physical properties since, as can be seen from the preceding sections, electrical tests must be applied to determine the effects of temperature, humidity, and solvents. Moreover, an electrical property like current-carrying capacity is almost entirely determined by the temperature limitations of the insulation.

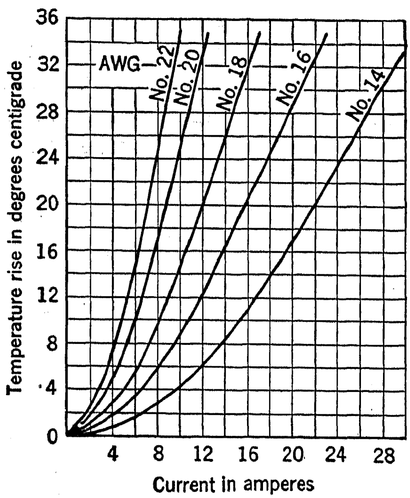


FIG. 1·2.—Temperature rise vs. current.

Current-carrying Capacity and Voltage Drop.—There is little information available on the current-carrying capacity of the wire sizes generally used for radio hook-up applications, sizes AWG No. 14 to AWG No. 24. A considerable amount of standardization has been done by the AIEE on wire sizes used for commercial and house wiring, but the available tables are not carried to sizes smaller than AWG No. 14. This data is of some use, however, for calculations of conductors for filament or primary power if large numbers of tubes are utilized. Table 1·7 gives safe current-carrying capacities based on 30°C ambient temperature for wires insulated with polyvinyl chloride (National Electrical Code type SN, or JAN types WL, SRIR, SRHV). Some information has been obtained on smaller-size wires,[1] but only for a single conductor under conditions of semirestricted

[1] J. M. Caller, "Characteristics of Radio Wire and Cable," *Radio*, **28**, No. 5, pp. 25–28, p. 58; *Radio*, **28**, No. 6, pp. 28–31, p. 64, p. 66.

ventilation. The data is shown in Table 1·8 and applies to wire insulated with 0.025-in. wall extruded polyvinyl chloride. The data does not cover other insulating materials and liberal safety factors should be applied where conditions of reduced heat radiation are to be met, as in cabling, or due to enclosure in conduits. These factors can be estimated from Table 1·7.

TABLE 1·7.—CURRENT-CARRYING CAPACITY OF RADIO HOOK-UP WIRE
Insulation, Polyvinyl Chloride; Ambient Temperature, 30°C

Size, AWG	Dielectric thickness, in.	Current-carrying capacity, amp: Free air	Three conductors in cable	Eight conductors in cable
14	0.031	24	18	13
12	0.031	31	23	16
10	0.031	42	31	22
8	0.047	58	41	29
6	0.063	78	54	38

TABLE 1·8.—CURRENT-CARRYING CAPACITY OF SMALLER-SIZE WIRE*

Temperature rise, °C	Current, Amp: AWG No. 14	AWG No. 16	AWG No. 18	AWG No. 20	AWG No. 22	AWG No. 24	AWG No. 26	AWG No. 28
10	15	11	8	6	4.5	3.3	2.5	1.8
20	21.5	15.5	11.5	8.5	6.5	4.8	3.5	2.6
30	27.5	20	15	11	8.5	6.3	4.5	3.4

* See Fig. 1·2.

Voltage-drop calculations may be necessary for filament and primary power conductors. The values in Table 1·3 are maximum resistances per 1000 ft for solid and stranded wires up to size AWG No. 14 and for stranded wires from No. 14 to No. 6. It is to be noted that these values hold at 25°C and that for temperatures differing from this value over the range normally encountered a correction factor $[1 + \alpha(t - 25°)]$ must be applied. For soft annealed copper of 98 per cent conductivity, α at 25°C is 0.00378. Some uncertainties arise in determining the value of t for an insulated conductor since the thermal characteristics of the insulation affect the temperature of the wire itself. The refinement of such calculations fortunately is not often required.

Voltage Rating.—Three classifications of general-purpose hook-up wire based on maximum rms operating voltage are given in the JAN-C-76 specification:

Type	Volts rms
WL	600 or less
SRIR	1000 or less
SRHV	2500 or less

In Table 1·9 comparative diameters, dielectric-strength test voltages and spark test voltages are given for the standard range of wire sizes.

TABLE 1·9.—COMPARATIVE DIAMETERS, SPARK AND DIELECTRIC-STRENGTH TEST VOLTAGES

Wire size AWG	Diameter* OD, in.			Spark test† 60 cps rms, v			Dielectric strength, v,‡ 60 cps rms		
	WL	SRIR	SRHV	WL	SRIR	SRHV	WL	SRIR	SRHV
24	0.080	0.055	0.065	5000	5000	7,500	2000	3000	6000
22	0.090	0.066	0.076	5000	5000	7,500	2000	3000	6000
20	0.100	0.074	0.084	5000	5000	7,500	2000	3000	6000
18	0.115	0.089	0.099	5000	5000	10,000	2000	3000	6000
16	0.130	0.101	0.111	5000	5000	10,000	2000	3000	6000
14	0.150	0.127	0.137	5000	7500	15,000	2000	3000	6000
12	0.170	0.157	0.167	5000	7500	15,000	2000	3000	6000
10	0.200	0.190	0.200	5000	7500	15,000	2000	3000	6000
8	0.255	0.239	0.249	5000	7500	15,000	2000	3000	6000
6	0.310	0.283	0.293	5000	7500	15,000	2000	3000	6000

* For type WL, the OD is measured over the braided or extruded outer covering. The other types have only primary insulation.

† The spark test is run in a chain-electrode device that subjects the insulation to impulses of not less than 0.2 sec duration.

‡ The dielectric-strength test is run with 60 cps sine-wave voltage brought up to full test value in less than 1 min and maintained for 1 min.

Insulation Resistance.—Insulation resistance of hook-up wire is an important factor since in some cases it may be the limiting factor in high-impedance input circuits or it may give rise to leakage currents between circuits that are intended to be isolated. This is particularly true at the high temperatures, often more than 70°C, which electronic equipment frequently reaches. Minimum insulation resistance values at 15.5°C for the three types of wire described in the previous paragraph are:

Type	Minimum resistance value, megohms/1000 ft
WL	10
SRIR	100
SRHV	750

Measurements are made with a megohm bridge, or with a galvanometer and a d-c source of between 200 and 500 volts. The wire is

immersed in water and the conductor made negative with respect to the grounded container.

Some idea of the magnitude of the temperature effect on insulation resistance is given by the correction factors of Table 1·10, which are specified to normalize the measurements to 15.5°C.

TABLE 1·10.—TEMPERATURE CORRECTION FACTORS

Temperature, °C	Coefficient of insulation resistance
0	0.032
10	0.29
20	2.5
30	17.5
35	48.0

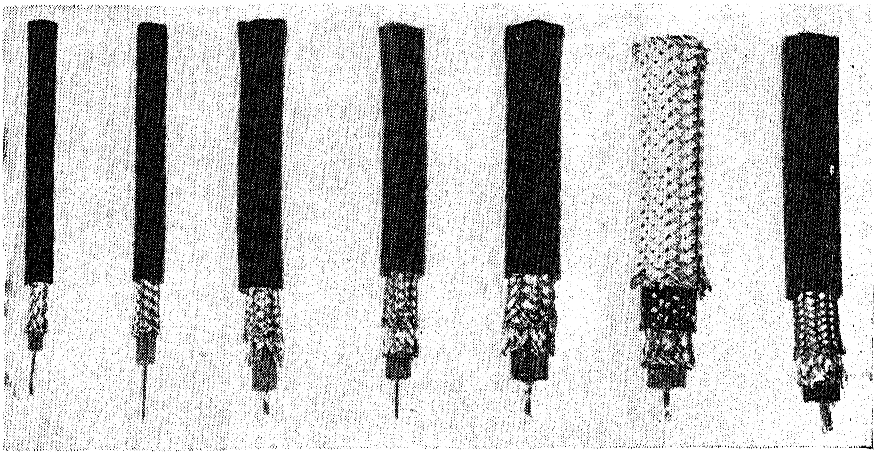
Dielectric Constant and Power Factor.—For general-purpose hook-up wire, no power-factor or dielectric-constant measurements are specified. There is one type of wire classified in JAN-C-76 as SRRF for which these characteristics are given. It is intended for radio-frequency applications at 1000 volts rms or less. The dielectric constant measured at 1 Mc/sec and over a temperature range of 20° to 60°C is limited to a maximum of 3.5. The power factor under the same conditions is limited to a maximum of 0.05. These values are easily met by the use of polyethylene insulation.

CABLES

The following sections will deal with the flexible coaxial transmission lines used for carrying video and i-f signals, CRT sweep currents and voltages, triggers, range marks, blanking pulses, and other signals that are associated with receiver and indicator circuits. The frequencies normally considered do not exceed 100 Mc/sec, and the voltages rarely exceed 1000 volts, peak. Although the frequencies are considerably lower than those required for r-f transmission and the voltages much less than used in modulator pulse cables, special considerations of impedance, capacitance, and shielding have led to the development of cables that form a group apart from either of these types. For example, present practice in r-f applications is limited to cables of 50 to 55 ohms impedance. For i-f and video transmission it is highly desirable for reasons of gain and bandwidth to use cables of at least 70 ohms impedance, and preferably higher, and with capacitances lower than that obtained in the 50-ohm lines. Cable capacitance is also important for sweep currents and voltages, triggers, and other signals, and special types of cable have been developed with capacitances of 10 to 14 $\mu\mu$f/ft. The problem of shielding between a mixer and i-f amplifier becomes important because of the very high gain in both the i-f and video ampli-

fiers and the consequent danger of pickup. Special cables with two woven metal braids are often required.

Under the wartime guidance of the Army-Navy R.F. Cable Coordinating Committee, development and standardization of cable types has



(a) (b) (c) (d) (e) (f) (g)

FIG. 1·3.—R-f cable: (a) RG-58/U; (b) RG-59/U; (c) RG-5/U; (d) RG-6/U; (e) RG-13/U; (f) RG-12/U; (g) RG-9/U.

attained an excellence and simplicity to be found in few, if any, other radio components. Much of the data in this section has been obtained from publications credited to that group, directly or indirectly.[1]

The cables to be discussed consist of

1. A group of cables having characteristic impedance of 70 to 80 ohms, ranging in size from 0.242 to 0.475 in. over-all diameter, with single and double shielding braids.
2. A group of low-capacitance cables, capacitance 10 to 13.5 $\mu\mu$f/ft, impedance from 90 to 125 ohms, varying in size from 0.242 to 0.405 in., with single and double shielding braids.
3. A high-impedance cable having a characteristic impedance of 950 ohms, intended for video applications.

These cables are listed and their characteristics summarized in Table 1·11. A number of standard cables are illustrated in Fig. 1·3.

1·6. The Conductor. *Stranded Copper.*—Stranded tinned copper wire is used for cable types RG-11/U and its modifications, RG-12/U and RG-13/U. Seven strands of No. 26 AWG with a nominal strand

[1] Joint Army-Navy Specification JAN-C-17A, July 25, 1946, Cables, Coaxial and Twin-Conductor, for Radio Frequency. (Army No. 71-4920A; Navy No. 16C8c.) See also the *Standard Components List* of the Army-Navy Electronics Standards Agency, Red Bank, N. J.

TABLE 1·11.—ARMY-NAVY STANDARD LIST OF R-F CABLES

Class of cables	Army-Navy type number	Inner conductor	Dielectric material*	Nominal diameter of dielectric, in.	Shielding braid	Protective covering	Nominal OD, in.	Weight, lbs/ft.	Nominal impedance, ohms	Nominal capacitance, μμf/ft.	Max. operating voltage, rms	Remarks
50–55 ohms												
Single braid	RG-58/U	20 AWG copper	A	0.116	Tinned copper	Vinyl	0.195	0.025	53.5	28.5	1900	General-purpose small-size flexible cable
	RG-8/U	7/21 AWG copper	A	0.285	Copper	Vinyl	0.405	0.106	52.0	29.5	4000	General-purpose medium-size flexible cable
	RG-10/U	7/21 AWG copper	A	0.285	Copper	Vinyl (noncontaminating) and armor	(Max.) 0.475	0.146	52.0	29.5	4000	Same as RG-8/U armored for Naval equipment
	RG-17/U	0.188 copper	A	0.680	Copper	Vinyl (noncontaminating)	0.870	0.460	52.0	27.5	11,000	Large high-power low-attenuation transmission cable
	RG-18/U	0.188 copper	A	0.680	Copper	Vinyl (noncontaminating) and armor	(Max.) 0.945	0.585	52.0	29.5	11,000	Same as RG-17/U except armored for Naval equipment
	RG-19/U	0.250 copper	A	0.910	Copper	Vinyl (noncontaminating)	1.120	0.740	52.0	29.5	14,000	Very large high-power low-attenuation transmission cable
	RG-20/U	0.250 copper	A	0.910	Copper	Vinyl (noncontaminating) and armor	(Max.) 1.195	0.925	52.0	29.5	14,000	Same as RG-19/U except armored for Naval equipment
Double braid	RG-55/U	20 AWG copper	A	0.116	Tinned copper	Polyethylene	(Max.) 0.206	0.034	53.5	28.5	1900	Small-size flexible cable
	RG-5/U	16 AWG copper	A	0.185	Copper	Vinyl	0.332	0.087	53.5	28.5	2000	Small microwave cable
	RG-9/U	7/21 AWG silvered copper	A	0.280	Inner, silver-coated copper; outer, copper	Vinyl (noncontaminating)	0.420	0.150	51.0	30.0	4000	Medium-size, low-level circuit cable

TABLE 1·11.—ARMY-NAVY STANDARD LIST OF R-F CABLES.—(*Continued*)

Class of cables	Army-Navy type number	Inner conductor	Dielectric material*	Nominal diameter of dielectric, in.	Shielding braid	Protective covering	Nominal OD, in.	Weight, lbs/ft.	Nominal impedance, ohms	Nominal capacitance, μμf/ft.	Max. operating voltage, rms	Remarks
	RG-14/U	10 AWG copper	A	0.370	Copper	Vinyl (noncontaminating)	0.545	0.216	52.0	29.5	5500	General-purpose semi-flexible power transmission cable
	RG-74/U	10 AWG copper	A	0.370	Copper	Vinyl (noncontaminating) and armor	0.615	0.310	52.0	29.5	5500	Same as RG-14/U except armored for Naval equipment
70–80 ohms												
Single braid	RG-59/U	22 AWG copperweld	A	0.146	Copper	Vinyl	0.242	0.032	73.0	21.0	2300	General-purpose small size video cable
	RG-11/U	7/26 AWG tinned copper	A	0.285	Copper	Vinyl	0.405	0.096	75.0	20.5	4000	Medium-size flexible video and communication cable
	RG-12/U	7/26 AWG tinned copper	A	0.285	Copper	Vinyl (noncontaminating) and armor	0.475	0.141	75.0	20.5	4000	Same as RG-11/U except armored for Naval equipment
Double braid	RG-6/U	21 AWG copperweld	A	0.185	Inner, silver-coated copper; outer; copper	Vinyl (noncontaminating)	0.332	0.082	76.0	20.0	2700	Small-size video and i-f cable
	RG-13/U	7/26 AWG tinned copper	A	0.280	Copper	Vinyl	0.420	0.126	74.0	20.5	4000	I-f cable
Cables of special characteristics												
Twin conductor	RG-22/U	2 Cond. 7. #18 AWG copper	A	0.285	Single; tinned copper	Vinyl	0.405	0.107	95.0	16.0	1000	Small-size twin-conductor cable
	RG-57/U	2 Cond. 7/21 AWG copperweld	A	0.472	Single; tinned copper	Vinyl	0.625	0.225	95.0	16.0	3000	Large-size twin-conductor cabie

High attenuation	RG-21/U	16 AWG resistance wire	A	0.185	Inner, silver-coated copper, outer, copper	Vinyl (noncontaminating)	0.332	0.087	53.0	29.0	2700	Special attenuating cable with small temperature coefficient of attenuation
High impedance	RG-65/U	No. 32 Formex F. helix diam, 0.128 in.	A	0.285	Single; copper	Vinyl	0.405	0.096	950	44.0	1000	High-impedance video cable; see Sec. 1·12.
Low capacitance; Single braid	RG-62/U	22 AWG copperweld	A	0.146	Copper	Vinyl	0.242	0.0382	93.0	13.5 Max. 14.5	750	Small-size low-capacitance air-spaced cable
	RG-63/U	22 AWG copperweld	A	0.285	Copper	Vinyl	0.405	0.0832	125	10.0 Max. 11.0	1000	Medium-size low-capacitance air-spaced cable
Double braid	RG-71/U	22 AWG copperweld	A	0.146	Inner, plain copper; outer, tinned copper	Polyethylene	0.250 (Max.)	0.0457	93.0	13.5 Max. 14.5	750	Small-size low-capacitance air-spaced cable for i-f purposes
Pulse applications; Single braid	RG-26/U	19/0.0117 tinned copper	D	†0.308	Tinned copper	Synthetic rubber and armor	(Max.) 0.525	0.189	48.0	50.0	8000 (peak)	Medium-size pulse cable armored for Naval equipment
	RG-27/U	19/0.0185 tinned copper	D	†0.455	Single, tinned copper	Vinyl and armor	(Max.) 0.675	0.304	48.0	50.0	15,000 (peak)	Large-size pulse cable armored for Naval equipment
Double braid	RG-64/U	19/0.0117 tinned copper	D	†0.308	Tinned copper	Neoprene	0.495	0.205	48.0	50.0	8000 (peak)	Medium-size pulse cable
	RG-25/U	19/0.0117 tinned copper	D	†0.308	Tinned copper	Neoprene	0.565	0.205	48.0	50.0	8000 (peak)	Special twisting pulse cable for Naval equipment
	RG-28/U	19/0.0185 tinned copper	D	†0.455	Inner, tinned copper; outer, galvanized steel	Synthetic rubber	0.805	0.370	48.0	50.0	15,000 (peak)	Large-size pulse cable
Twisting application Single braid	RG-41/U	16/30 AWG tinned copper	C	0.250	Tinned copper	Neoprene	0.425	0.150	67.5	27.0	3000	Special twist cable

* Dielectric Materials
A Stabilized Polyethylene
C Synthetic rubber compound
D Layer of synthetic rubber dielectric between thin layers of conducting rubber.
† This value is the diameter over the outer layer of conducting rubber.

diameter of 0.0159 in. make up a No. 18 AWG conductor, further details of which are given in Table 1·11.

Copperweld.—In order to obtain cables of smaller size but with the same or higher impedance than the above, the size of the center conductor must be reduced in accordance with the following expressions for impedance and capacitance per unit length of a coaxial line:

$$Z_0 = \frac{138}{\sqrt{\epsilon}} \log_{10} \frac{a}{b} \qquad \text{ohms,}$$

and

$$C = \frac{24 \times 10^{-12}\epsilon}{\log_{10} \frac{a}{b}} \qquad \text{farads per meter,}$$

where ϵ = dielectric constant of insulation,
a = diameter of outer conductor,
b = diameter of inner conductor.

This reduction is accomplished by the use of a center conductor that is a copper-covered steel wire fabricated by a process that welds the copper continuously to the steel core. This results in a composite conductor having the high tensile strength of the steel core and the good conductivity of its copper sheath. Data for 30 per cent conductivity grade solid copperweld wire of the sizes used in cable designs are given in Table 1·12. These data apply to the grade specified in JAN-C-17 which has the following characteristics:

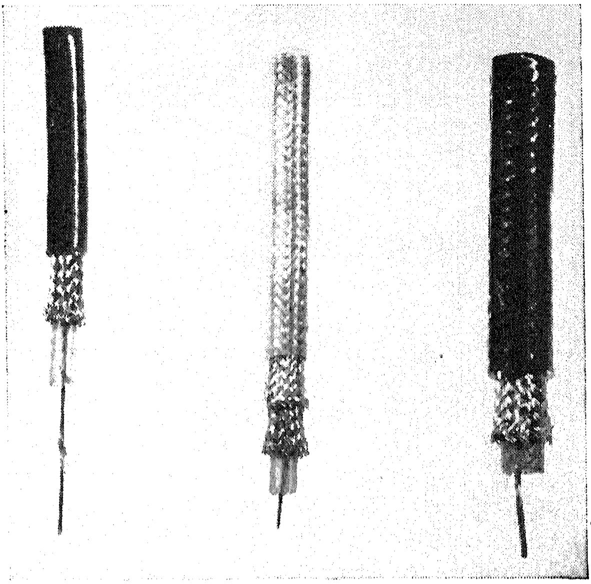
Grade	high strength, 30 per cent conductivity.
Tensile strength	not less than 127,000 lb/in².
Elongation	not less than 1 per cent in 10 in.
Maximum resistivity	39.18 ohms per circular mil-ft (20°C).
Diameter tolerance	±0.5 mils for diameters from 0.020 to 0.035 in. ±1.0 mil for diameters from 0.035 to 0.060 in.

TABLE 1·12.—SOLID COPPERWELD WIRE (30 PER CENT CONDUCTIVITY) DATA

Size, AWG	Diameter, in.	Cir mils	Area, in.²	Weight, lb/1000 ft	Resistance, ohms/1000ft	Tensile strength, lb
16	0.0508	2583	0.002028	7.167	13.65	270
17	0.0453	2048	0.001609	5.684	17.22	205
18	0.0403	1624	0.001276	4.507	21.71	170
19	0.0359	1288	0.001012	3.575	27.37	135
20	0.0320	1022	0.0008023	2.835	34.52	110
21	0.0285	810.1	0.0006363	2.248	43.52	81.1
22	0.0253	642.5	0.0005046	1.783	54.88	64.3
23	0.0226	509.5	0.0004001	1.414	69.21	51.0
24	0.0201	404.0	0.0003173	1.121	87.27	40.4

The small-size 75-ohm cables, RG-59/U and RG-6/U, have a center conductor of No. 22 AWG and No. 21 AWG, respectively. The low-capacitance cables, RG-63/U, RG-62/U, and RG-71/U have a center conductor of No. 22 AWG.

Wound-center Conductor.—In order to match the load impedance of video amplifiers, a special high-impedance cable has been designed with a characteristic Z_0 of 950 ohms. Such a cable offers considerable advantage where the length of run is not so great that the attenuation, which



(a) (b) (c)

FIG. 1·4.—Low-capacitance r-f cable: (a) RG-62/U; (b) RG-71/U; (c) RG-63/U.

is considerably higher than for conventional cables, does not cancel the gains to be derived from matching to high load resistance. The RG-65/U cable is further described in Sec. 1·12.

Resistance Wire.—A few types of cables have been designed to have high losses, for use as attenuating or terminating devices. These losses may be introduced by using a high-resistance metal for the center conductor, as in RG-21/U cable, which has a center conductor of No. 16AWG Nichrome or similar alloy. Three types of high-attenuation cable are shown in Fig. 1·7. (The high losses of the RG-38/U are due to the use of a lossy rubber dielectric, not to a high-resistance center conductor.)

1·7. The Primary Insulation. *Solid Dielectric.*—The dielectric for all the cables treated in Secs. 1·6 through 1·11 is polyethylene, characteristics for which are given in Sec. 1·2. Polyethylene is, to date, by far the best available material from the standpoint of high-frequency

losses, flexibility, and temperature stability. In cable construction, it is extruded around the center conductor and is substantially free from voids or other imperfections. In general, it is required that the center conductor, after the extrusion process, should not be off center by more than 10 per cent of the core radius and that the diameter of the dielectric should not vary from a stated nominal value by more than ± 3.5 per cent or ± 0.015 in., whichever is smaller.

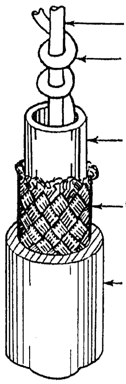


FIG. 1·5.—Section of RG-62/U cable.

Air-spaced Dielectric.—For the low-capacitance cables RG-63/U, RG-62/U, and RG-71/U (see Fig. 1·4) the core is constructed by wrapping the conductor with a polyethylene thread widely spaced between turns and covering this with an extruded tube of solid polyethylene as shown in Fig. 1·5. The effect of this wrap is to include a substantial amount of air in the space close to the conductor, thus lowering the effective capacitance of the cable. The reduction in capacitance can be seen by comparing two cables having identical physical dimensions; the solid dielectric RG-59/U and the semisolid air-spaced dielectric RG-62/U. The figures are 21.0 $\mu\mu$f/ft and 13.5 $\mu\mu$f/ft, respectively.

1·8. The Metal Braid. *Single Braid.*—The outer conductor is a woven metal braid, usually of plain or tinned No. 33 or 34 AWG copper wire. The mechanical requirements are that it ride tightly, evenly, and smoothly without piling on the surface of the dielectric material and without imbedding itself within the dielectric. Types RG-11/U, RG-12/U, RG-59/U, RG-63/U, RG-62/U, and RG-65/U are single-braid cables.

Double Braid.—For i-f applications, a single braid is insufficient to prevent pickup at the frequencies and signal levels usually used. For such use, double-shielded cables (such as RG-13/U, RG-6/U, and RG-71/U,) are required. The braid may be a double copper braid (RG-13/U), a silver-coated copper inner braid under a plain copper outer braid (RG-6/U) or double tinned copper braid (RG-71/U). There is some preference for a tinned-copper outer braid rather than a plain copper outer braid because it is less subject to corrosion and less difficult to handle in soldering. The argument for silver-coated inner braid is that it seems to have greater stability for high-frequency use. The data on braids and shielding is not yet complete enough for the formulation of conclusive recommendations.

1·9. The Outer Covering.—For mechanical protection and sealing against the entrance of moisture, the outer braid is covered with a tough, flexible jacket of polyvinyl chloride or polyethylene. For particularly

severe usage, the jacket may then be covered with a metal armor, as in the RG-12/U cable.

The Jacket.—Plasticized polyvinyl chloride or plasticized vinyl chloride-vinyl acetate copolymers have excellent characteristics for jacketing purposes. Their resistance to abrasion, flexibility at low temperature, resistance to ozone, sunlight, and oil and other chemicals are all sufficiently good to make such materials the most satisfactory available at present. It has been found, however, that a special plasticizer must be used to prevent contamination of the polyethylene dielectric with aging and use, particularly at elevated temperatures. This contamination or "poisoning" results in increased cable losses which may seriously affect the performance of the over-all system at microwave frequencies if long cables are part of the interconnections. The JAN specifications call for such a noncontaminating jacket on types RG-6/U and RG-12/U. It is interesting to note that the contamination test consists of heating the cable for seven days at 98°C, after which the attenuation at 3000 Mc/sec is to be not greater than 2 db/100 ft more than the initial value. The standard vinyl jacket is referred to in this specification as Type I, the noncontaminating type as Type II.

Where minimum size is a consideration, it is sometimes desirable to use a thin extruded sheath of polyethylene as a protective jacket. Polyethylene has physical properties as good or better than the vinyl polymers but it is not as good with respect to flammability or oil resistance. For internal wiring or interconnections between chassis in a protected equipment, polyethylene jackets may be the material of best choice. Such a jacket is used in RG-71/U.

Metal Armor.—A metal armor may be used over the plastic jacket where particularly severe military conditions are to be met. The Navy specifies such armor for many of its shipboard equipment installations, calling for a braided metal armor of galvanized steel wire, painted with aluminum paint.

1·10. Physical Properties of the Finished Cable. *High Temperature.*—Polyethylene and vinyl polymers have definite limitations at high temperatures, particularly if at the same time there is heavy mechanical loading due to flexing or to the weight of long lengths of cable. Displacement of the center conductor may take place under such conditions if the conductor temperature is much above 85°C, the normal safe maximum operating temperature for a conductor in a polyethylene dielectric.

The flow characteristic is specified for various cables by giving the value of a weight to be hung at the ends of the center conductor of a cable suspended over a mandrel 10 times the cable diameter. After $7\frac{1}{2}$ hr at 98°C it is required that the center conductor shall not be displaced by more than 15 per cent of the diameter of the dielectric.

If elevated temperatures are sustained, heat-aging changes may take place in both the dielectric and the jacket, rendering the plastics brittle and subject to cracking when flexed. A heat-aging test is specified which calls for subjecting the cable to seven days operation at 98°C after which the cable is wound and unwound ten times over a mandrel ten times the cable diameter. After such a test the dielectric material and the outer protective covering are expected to be free from signs of cracking or loss of pliability.

Low Temperature.—At very low temperatures the materials in the dielectric and covering may become brittle and subject to cracking when flexed. There has been considerable progress in improving the low-temperature pliability of these materials and, at present, they can be used at −40°C with no special precautions. A cold bending test is specified which calls for cooling to −40°C and immediately bending the cable 180° around a mandrel of a diameter ten times the cable diameter. After this test, the dielectric and outer covering are expected to show no signs of cracks or fractures.

Moisture and Solvents.—Polyethylene and vinyl compounds are practically immune to moisture if suitable plasticizers are used in their formulation. The vinyl jacket has excellent chemical resistance to gasoline or oil; the resistance of the polyethylene is only fair. A test is specified which calls for immersion of the cable, except for the exposed ends, in 100-octane aviation-type gasoline for 4 hr at room temperature. At the end of this time, it is expected that there will be no evidence of liquid penetration through the jacket.

1·11. Electrical Properties of the Finished Cable. *Impedance and Capacitance.*—The properties of particular interest in the choice and use of cables for video and i-f applications are impedance, capacitance, and attenuation. For example, in 30-Mc/sec i-f links between the crystal mixer and the i-f amplifier, low capacitance and high impedance are desirable even though the line may be only 6 to 12 in. long. Ideally, the impedance should approach 300 ohms, the order of magnitude of the mixer output impedance, but because no such cables are at present available it is customary to use 73-ohm or 93-ohm types. Capacitance of i-f cable is a major problem in broadband i-f circuits where the input circuit must have a bandwidth of 12 to 15 Mc/sec if the over-all bandwidth is to be 6 to 8 Mc/sec. It has been found that even very short lengths of i-f cable present complications in these circuits because they cannot be treated as lumped constants. Trial-and-error adjustments of the input circuit are required for optimum performance.

The length of the cable was not critical for the older type of i-f circuit, in which the mixer was followed by a preamplifier and the i-f amplifier was almost always at some considerable distance from the pre-

amplifier, because an untuned input circuit was used. It was customary simply to use a 73-ohm input terminating resistor. For this type of installation, lines of higher impedance which were not then available would have resulted in better over-all gain and bandwidth by permitting a larger shunt resistor at the input circuit, thus increasing the available voltage. RG-71/U cable with an impedance of 93 ohms and a capacitance of 13.5 $\mu\mu$f/ft, double shielded, is one of the two cables particularly applicable to i-f uses. The other is RG-6/U with an impedance of 76 ohms and a capacitance of 20 $\mu\mu$f/ft, also double shielded.

In the transmission of video signals, cathode-ray-tube sweep currents and voltages, triggers, blanking pulses, and other signals associated with receiver and indication circuits, cable capacitance is advantageously kept to a minimum since lengths of cable up to several hundred feet are frequently required. Air-spaced dielectric cables such as RG-63/U and RG-62/U are most often used. The first has a capacitance of 10 $\mu\mu$f per foot, and an impedance of 125 ohms; the second, a capacitance of 13.5 $\mu\mu$f per foot, and an impedance of 93 ohms. A special type of high-impedance cable for video use utilizes a wound center conductor, as has been mentioned in Sec. 1·6. Complete information on this cable, type RG-65/U, is given in Sec. 1·12.

Attenuation.—The attenuation of polyethylene cables at video and i-f frequencies is fairly low. None of the cables discussed here, with the exception of RG-65/U, has an attenuation greater than 2 to 4 db/100 ft

TABLE 1·13.—ATTENUATION AND VOLTAGE CHARACTERISTICS OF R-F CABLES

Cable type	Attenuation, db/100 ft		Rms voltages, kv	
	At 10 Mc/sec	At 100 Mc/sec	Operating, max	Test
RG-11/U RG-12/U RG-13/U	0.5*	2.1	4.0	10
RG-59/U	1.0	3.8	2.3	7
RG-6/U	0.7*	2.8	2.7	7
RG-62/U RG-71/U	1.0	3.1	0.75	3
RG-63/U	0.6	2.0	1.0	3
RG-65/U	21.5	....	1.0	3

* Estimated.

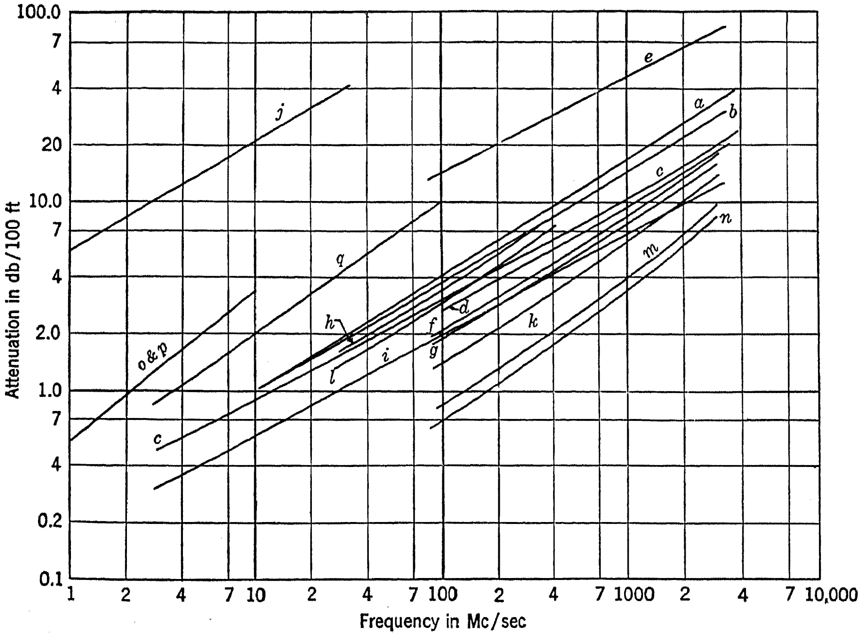
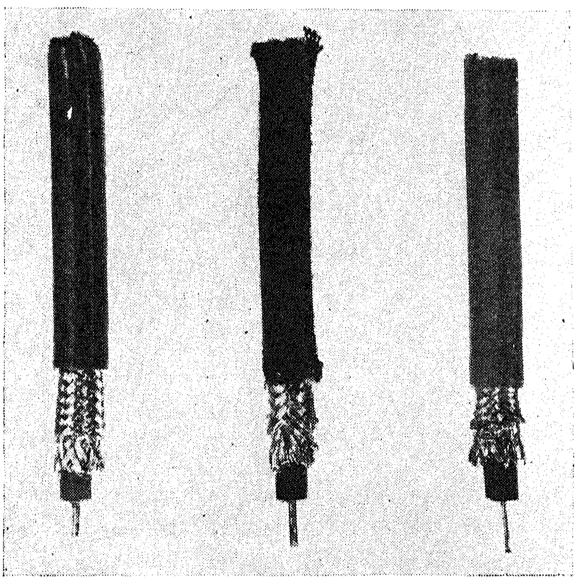


FIG. 1·6.—Attenuation of standard r-f cables vs. frequency. Cable RG-/U number: (*a*) 55 and 58; (*b*) 59; (*c*) 62 and 71; (*d*) 5 and 6; (*e*) 21; (*f*) 8, 9, and 10; (*g*) 11, 12, and 13; (*h*) 22; (*i*) 63 and 79; (*j*) 65; (*k*) 14 and 74; (*l*) 57; (*m*) 17 and 18; (*n*) 19 and 20; (*o*) 25, 25A, 26, 26A, 64, 64A, 77, 78; (*p*) 27 and 28; (*q*) 41.



(*a*) (*b*) (*c*)

FIG. 1·7.—High-attenuation r-f cable: (*a*) RG-21/U; (*b*) RG-38/U; (*c*) KS 8086.

at 100 Mc/sec. Comparative figures are given in Table 1·13 for attenuation in db per 100 ft at 10 and 100 Mc/sec. More extensive data for all the standard r-f cables are given in Fig. 1·6. Figure 1·7 is a photograph of three high-attenuation r-f cables.

Dielectric Strength.—The voltage ratings of the cables discussed previously are well above the maximum values generally required. CRT deflection voltages are perhaps the only case where the dielectric is subjected to an appreciable fraction of its rated voltage. The medium size 75-ohm cables are rated at 4000 volts, rms; the small size RG-59/U and RG-6/U at 2300 and 2700 volts, rms; the semisolid low-capacitance cables at 750 or 1000 volts, rms. A dielectric strength test is specified in which an a-c voltage (sine form, 15 to 65 cps) is applied to the cable for 60 sec.

1·12. High-impedance Cable.[1]—High-impedance cables may be used for the transmission of video signals over distances of approximately 1 to 100 ft.

Present-type video amplifiers are built with load impedances of about 1000 ohms. Ordinary coaxial cables have impedances of 50 to 100 ohms and capacitances of 10 to 30 $\mu\mu$f/ft. They may be matched to correspondingly low load resistances, or they may be treated as lumped load capacitances. In either case the cable load lowers the peak voltage output and gain available from a given tube.

To avoid these losses cables with much higher surge impedance have been developed. Their design is derived from that used for delay lines of the distributed-parameter type, but their dimensions are chosen so as to yield a high impedance with the least possible signal delay and attenuation per unit length. The less the signal delay in the cable, the more accurate will be the isochronism of the separate units and the less will be the spacing of spurious echoes from improper terminations.

Electrical Characteristics.—In any line the surge impedance Z is

$$Z = \sqrt{\frac{L}{C}} \tag{1}$$

and

$$Z = \frac{T}{C} \tag{2}$$

where

L is the inductance per unit length,
C is the capacitance per unit length,
T is the delay per unit length.

[1] The material given in this section has been published by the author; H. E. Kallmann, "High-Impedance Cable," *Proc. IRE*, **34**, 348–351 (June 1946).

In order to make the impedance Z high and the delay T low, the inductance L should be made large and the capacitance C kept small. In high-impedance cable, inductance is increased by replacing the straight inner conductor of the ordinary coaxial cable by a close-wound continuous coil of insulated wire, and capacitance is kept low by using wide spacing between the inner and outer conductor and by using a low-dielectric constant material as spacer.

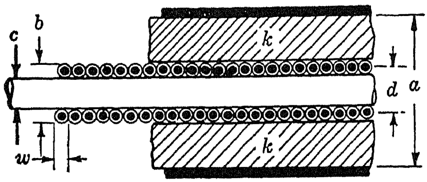


FIG. 1·8.—Essential dimensions of high-impedance cable.

The approximate computation of the inductance, capacitance, impedance, and delay of a high-impedance cable may be carried out as follows. Referring to Fig. 1·8, the inductance L of a continuously wound single-layer coil will be

$$L = 10^{-11}\pi^2 n^2 d^2 \qquad \text{henries per meter.} \tag{3}$$

The capacitance C of a concentric cable will be

$$C = \frac{24 \times 10^{-12}k}{\log_{10}\left(\frac{a}{b}\right)} \qquad \text{farads per meter.} \tag{4}$$

From Eqs. (1), (3) and (4) Eq. (5) for the impedance Z follows:

$$Z = \sqrt{\frac{10^{-11}\pi^2 n^2 d^2 \log_{10}\left(\frac{a}{b}\right)}{24 \times 10^{-12}k}} = \frac{\pi n d}{\sqrt{2.4k}} \sqrt{\log_{10}\left(\frac{a}{b}\right)}. \tag{5}$$

From Eqs. (2), (3), and (4), Eq. (6) for the time delay T follows:

$$T = 10^6 \sqrt{\frac{24 \times 10^{-23}\pi^2 n^2 d^2 k}{\log_{10}\left(\frac{a}{b}\right)}} = \frac{10^{-5}\,\pi d n \sqrt{2.4k}}{\sqrt{\log_{10}\left(\frac{a}{b}\right)}} \qquad \mu\text{sec.} \tag{6}$$

With negligible error, the surface of the coiled inner conductor is assumed to be a cylinder of diameter b. Then

$$b = d + w \tag{7}$$

and the core diameter is

$$c = d - w. \tag{8}$$

The design of a cable starts with the choice of the largest practicable outer diameter, for it follows from Eqs. (5) and (6) that the impedance Z rises and the delay T decreases as the outer diameter a is increased. The cable may have an outer diameter as large as 0.405 in. and still fit a

$\frac{3}{8}$-in. connector. Allowing for a protecting jacket and the thickness of the outer conductor, the following example is computed for a diameter $a = 0.78$ cm (0.308 in.) and for a solid dielectric spacer of polyethylene with dielectric constant $k = 2.25$. Both the impedance and the delay could be improved by $1/\sqrt{k}$ if the effective dielectric constant were reduced, for example by insertion of a helical spacer.

The impedance and the delay, as computed from Eqs. (5) and (6) for $a = 0.78$ cm (0.308 in.) and $k = 2.25$, are plotted in Fig. 1·9 and Fig. 1·10 as functions of the core diameter c. Three curves are presented

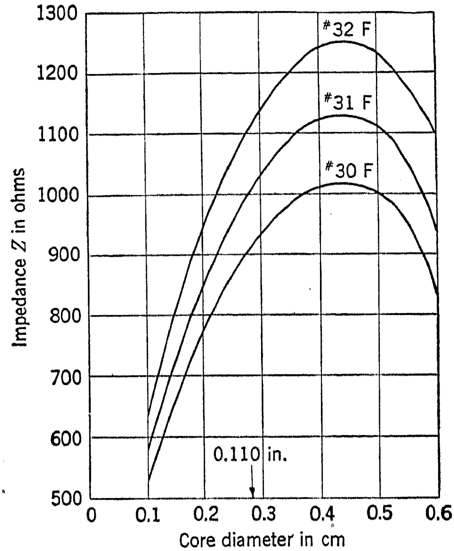


FIG. 1·9.—Cable impedance vs. core diameter.

$$Z = \frac{\pi n(c + w)}{\sqrt{2.4k}} \sqrt{\log_{10}\left(\frac{a}{c + 2w}\right)}$$

in each case. They are computed for coiled inner conductors close-wound with three different wire gauges.

1. Formex copper wire AWG No. 30F, with $w = 0.0108$ in.
2. Formex copper wire AWG No. 31F, with $w = 0.0099$ in.
3. Formex copper wire AWG No. 32F, with $w = 0.0089$ in.

Figure 1·9 shows that in all cases the impedance Z goes through a maximum, rising at first linearly with $d = c + 2w$ in the numerator of Eq. (5), and then eventually falling with $\sqrt{\log_{10}[a/(c + 2w)]}$. As can be seen the maximum is reached in each case at approximately the same value of the core diameter c. If the thickness of the wire w is negligible in comparison with the coil diameter d, so that $d \approx b$, then it can be shown that the maximum impedance is always reached for

$$\frac{a}{d} = \sqrt{e} \approx 1.65;$$

thus for $a = 0.78$ cm the highest impedance is obtained with

$$d = 0.475 \text{ cm and } c = 0.45 \text{ cm}.$$

Judging from Fig. 1·9 a value of c at or near 0.45 cm would be the preferred choice for this yields maximum impedance and in addition maintains the impedance unchanged with large variations of the core diameter. The following factors, however, are opposed to this choice.

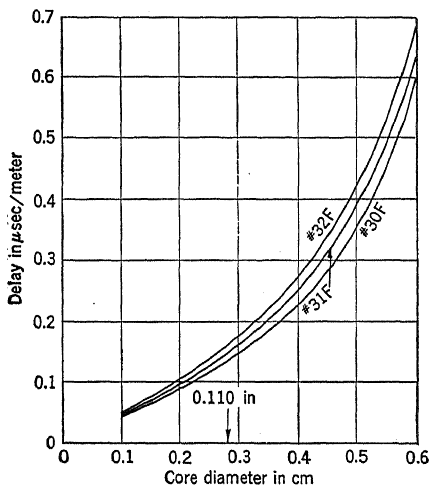


FIG. 1·10.—Delay vs. core diameter.

$$T_{\mu\ \mathrm{sec/meter}} = \frac{10^{-5}\pi n d\ \sqrt{2.4k}}{\sqrt{\log_{10}\left(\dfrac{a}{c+2w}\right)}}.$$

1. As shown in Fig. 1·10 the delay per unit length of cable rises rapidly with the diameter of the core due both to the increased coil diameter (increased inductance) and to the closer spacing of the conductors (increased capacitance). Furthermore, the larger the delay, the larger will be the spacing of echoes due to improper terminations.
2. The transmission loss A due to the ohmic resistance R in the coil is given by

$$A = \frac{4.35R}{Z}, \tag{9}$$

and A rises with the length of the wire which is proportional to the core diameter.

3. Parts of the magnetic field around the coiled inner conductor will cause eddy current losses in the closed turn of the outer conductor unless the outer conductor is either far enough away or braided of separately insulated wires.

A suitable compromise value for the core diameter is $c = 0.28$ cm (0.110 in.), (indicated in Figs. 1·9 and 1·10). This choice of c yields an impedance that is only 89 per cent of the maximum value, but it reduces the corresponding delay to 49 per cent of the value that is obtained for $c = 0.45$ cm and it reduces the coil resistance to 65 per cent. The outer conductor has a diameter 2.8 times that of the coil which is sufficiently large so that eddy current losses are small.

It may be noted that the core diameter c so determined depends only on the outer diameter a and its choice is not affected, for example, if another impedance is specified. Figure 1·9 shows that in such cases choice of a different wire gauge, wound on the same core diameter is the only change required. The impedance Z rises by over 10 per cent each time the wire gauge is made one AWG number finer; the delay rises in the same proportion but the transmission loss A rises by about 20 per cent.

A cable based on this design is manufactured[1] as the type RG-65/U, (see Fig. 1·11). Its specifications are:

Core; polyethylene 0.110 ± 0.010 in. in diameter.
Inner conductor; close-wound helix of AWG No. 32 copper wire.
Spacer; solid polyethylene extruded to 0.285 ± 0.010 in. in diameter.

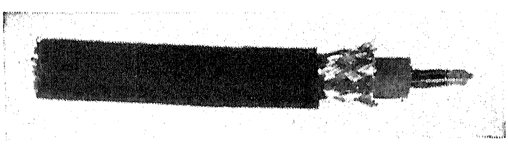


FIG. 1·11.—RG-65/U high-impedance cable.

Outer conductor; single-braid, plain copper wire No. 33 AWG, max. diameter 0.340 in.
Jacket; polyvinyl to overall diameter 0.405 ± 0.010 in.
Surge impedance; $Z = 950 \pm 50$ ohms.
D-c resistance; 7.0 ohms/ft.
Capacitance; 42 $\mu\mu$f/ft.
Delay; 0.042 μsec/ft at 5 Mc/sec.
Maximum operating voltage; 3000 volts rms.
Attenuation; 5.5 db/100 ft at 1 Mc/sec.
10.2 db/100 ft at 3 Mc/sec.
14 db/100 ft at 5 Mc/sec.
21.5 db/100 ft at 10 Mc/sec.
40 db/100 ft at 30 Mc/sec.

[1] By the Federal Telegraph and Radio Corp., in Newark, N. J.

The decrease in time delay with increasing frequency is small. The delay measured on a preproduction sample of about 1200 ohms impedance was found to drop steadily about 0.032 per cent per Mc/sec so that at 20 Mc/sec it had fallen to 99.35 per cent of that for the lowest frequencies.

Through choice of $a/b < \sqrt{e}$, the cable RG-65/U is deliberately designed for low signal delay per unit length. It is not meant to be used as a delay line. However, cables of similar construction but with $a/b > \sqrt{e}$ have been designed for use as delay lines in special applications (Chap. 6).

Terminating the Inner Conductor.—In order to attach connectors reliably to the inner conductor of high-impedance cables, the following procedure is suggested:

1. Cut back the jacket and push back braid, then remove dielectric spacer to clear $\frac{3}{8}$ in. of the coiled inner conductor.
2. Unwind $\frac{3}{16}$ in. of the coil, cut free wire down to 1 in., remove Formex insulation with emery cloth, and tin wire.
3. With a pair of pliers squeeze the exposed stub of the polyethylene core to about one-half of its original thickness.
4. Punch a hole at least $\frac{1}{32}$ in. wide with a needle (scriber) through the middle of the flattened portion.
5. Bend one end of 2-in. tinned copper wire (No. 20 to No. 22 AWG) to U shape around $\frac{1}{16}$ in. diameter and hook through the hole.
6. Wrap the tinned end of inner conductor two or three times around the short end of the hook, and solder.
7. With the heat of soldering the flattened end of the polyethylene core will melt and form a drop around the U-shaped wire hook. Hold the latter in place until the drop has hardened.

This procedure has proved both simple and reliable. The free end of the wire hook can be inserted into any of the usual connectors and soldered to them. The tensile strength of the hook-and-polyethylene weld is considerable and strain on the coiled conductor is taken up by a harmless elongation of the helix. The method is illustrated in Fig. 1·12.

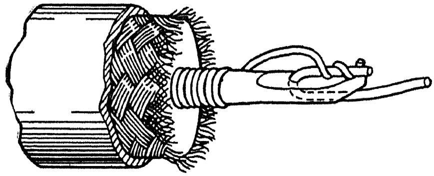


FIG. 1·12.—Method of terminating inner conductor.

CHAPTER 2

FIXED COMPOSITION RESISTORS

By G. Ehrenfried

The various types of fixed resistors form the subject matter of the next two chapters. Chapter 2 is devoted entirely to general-purpose fixed composition resistors which conform or nearly conform to the specifications of JAN-R-11. Chapter 3 discusses various types of standard or near-standard fixed wire-wound resistors and also a number of special types of resistors, both wire-wound and otherwise. As in most of the chapters of this volume, special emphasis is given to types conforming to ANESA specifications because of the concern of the Radiation Laboratory with military equipment.

2·1. The Choice of a Resistor.—Resistors are among the components most widely used in electronic circuits and may be classified into two main categories: composition resistors and wire-wound resistors. If the requirements are not such as to demand one or the other type, composition resistors are usually employed because of their cheapness and compactness. For more stringent requirements the choice is usually based upon one or more of the following factors.

Size.—A composition resistor for a certain job is often much smaller than a wire-wound resistor for the same job. This difference is most marked in high resistance values and in low dissipation ratings because the thinnest wire that can be used to make a reasonably rugged wire-wound resistor still has such low resistance per foot that a large amount of it must be used.

High-frequency Properties.—Composition resistors of low wattage ratings and medium resistance values can be considered as having practically pure resistances well up into the megacycle region. At high frequencies a small wire-wound resistor has a reactance that is of the same order of magnitude as the resistance itself.

Stability.—The chief disadvantage of composition resistors is their tendency to change in resistance when subjected to changing conditions. They do not, in general, return to their initial values after cycles of change. This lack of stability is a fatal disadvantage in many applications in which resistors are used in accurate measuring circuits.

Noise.—A composition resistor generates a considerable noise when a current flows through it; a wire-wound resistor, however, does not. This

difference makes inadvisable the use of composition resistors in low-level circuit applications.

Power-dissipating Ability.—Composition resistors are seldom used for dissipations of more than 2 watts, and are practically never used for dissipations of over 5 watts. Wire-wound resistors are available with dissipation ratings up to 200 watts per unit. Wire-wound resistors are usually capable of operating at higher temperatures than composition resistors—up to several hundred degrees centigrade in many cases.

Accuracy.—Because of their instability few composition resistors are furnished in tolerances closer than 5 per cent. Wire-wound resistors are regularly stocked in tolerances down to $\frac{1}{4}$ per cent, and may be obtained down to 0.05 per cent on special order. Wire-wound resistors, unlike composition resistors, may also be obtained in constructions that have little change of resistance with changing temperature or other conditions.

To sum up, wire-wound resistors are usually demanded by applications with rigid stability or accuracy requirements, or if powers of over a few watts must be dissipated. Composition resistors are usually used for less critical applications; if high frequencies, high resistance values, or a crowded chassis are involved, their advantages are marked.

2·2. Standards and Specifications; Coding and Labeling.—Until recently, the choice of resistors for specific applications was made difficult by differences between the ways in which manufacturers described their products and differences between the types of tests they used on them. The problem is considerably simplified now by the existence of standards that have been agreed upon by representatives of most resistor manufacturers and many users.

Two closely related sets of standards on fixed composition resistors have been in recent use by the electronic industry. The first is American War Standard C75.7-1943, approved Oct. 8, 1943, and issued by the American Standards Association, 70 E. 45th Street, New York City. Copies can be obtained from this organization for 60 cents apiece. The other is specification JAN-R-11, issued on May 31, 1944, by the Army-Navy Electronics Standards Agency, 12 Broad Street, Red Bank, N. J. This specification was issued mainly for use by those who make equipment for the armed services. It is derived from the American War Standard and is similar to it in most respects.

The differences between JAN-R-11 and AWS C75.7-1943 will be noted in appropriate places in this chapter. Attention should be called to two other documents connected with these standards. American War Standard C75.17-1944 entitled "Method of Noise-Testing Fixed Composition Resistors" is a description of the method of carrying out one of the tests prescribed in the AWS C75.7-1943 standard. This description was separated from the general resistor standard because it is fairly long

and is of interest mainly to those who make the test and not to those who use the resistors. Another document of interest is the proposed Amendment No. 1 to JAN-R-11. This amendment, if approved, will make two major changes in the specification and a number of minor changes.[1] The major changes are: addition of a new-style insulated resistor, RC-42, a two-watt style much smaller than those previously listed; and addition of a new characteristic symbol, G, covering insulated resistors that can be used at higher ambient temperatures than those of characteristics A, B, C, and D. Details on these changes will be given in appropriate places.

The AWS and JAN standards described here are not intended to cover all varieties of fixed composition resistors. Many special-purpose resistors are not included in their scope—for example, high-resistance power resistors consisting of a spiral band of carbon composition deposited on the outside of a ceramic tube. Even in cases like this where dimensions and structure depart from those of the standards, it is the custom to use the test procedures given in the standards wherever applicable as criteria by which to judge the quality of a resistor.

For further details the reader is referred to JAN-R-11 and to the other standards and specifications cited above. It should be noted that these works do not specify the high-frequency properties of resistors.

Standards Descriptive Code.—By specifying resistors according to the descriptive code included in the JAN standards a user can obtain from different manufacturers resistors that are for most purpose interchangeable with each other. This code consists of symbols using five letters and five numbers, which completely identify a resistor as to the following properties: dimensions, wattage rating at room temperature, presence or absence of insulating case, humidity and salt-water resistance, variation of resistance with temperature, resistance value, resistance tolerance. The type designation of a particular resistor breaks down as follows:

RC 10 AE 153 M

Component Style Characteristic Value Tolerance

Component: Fixed composition resistors are identified by the symbol "RC."

Style: The first two numbers identify the power rating, shape, and size as given in Table 2·1 and Fig. 2·1.

Characteristic: The next two letters identify the resistor as to its insulation, as to its resistance to humidity and salt-water-immersion

[1] At the time of writing it seems likely that this amendment will be changed somewhat before it is approved and issued.

TABLE 2·1.—JAN COMPOSITION-RESISTOR DIMENSIONS
Except as noted, all types have $1\frac{1}{2} \pm \frac{1}{8}$ in. leads and are made in resistance values from 10 ohms to 20 megohms

Type	Watts	Fig. 2·1, sketch	Maximum over-all length, in. A	Maximum over-all diameter, in. B	Minimum lead spacing, in. C	Minimum lead diameter, in.
RC-10	$\frac{1}{4}$	*a*	0.406	0.170	.....	0.028 (#21 AWG)
RC-15*	$\frac{1}{4}$	*b*	0.350	0.120	.....	0.016 (#26)
RC-16	$\frac{1}{4}$	*b*	0.655	0.248	0.376	0.028 (#21)
RC-20	$\frac{1}{2}$	*a*	0.468	0.249	.....	0.028
RC-21	$\frac{1}{2}$	*a*	0.655	0.249	.....	0.028
RC-25	$\frac{1}{2}$	*b*	0.780	0.280	0.407	0.032 (#20)
RC-30	1	*a*	0.750	0.280	.....	0.032
RC-31	1	*a*	1.28	0.310	.....	0.032
RC-35	1	*b*	1.16	0.280	0.814	0.036 (#19)
RC-38†	1	*b*	1.84	0.436	1.45	0.036
RC-40	2	*a*	1.41	0.405	.....	0.036
RC-41	2	*a*	1.78	0.405	.....	0.036
RC-45	2	*b*	2.12	0.592	1.45	0.036
RC-65	4	*b*	2.66	0.730	2.06	0.040 (#18)
RC-75	5	*b*	3.16	0.780	2.47	0.040
RC-76‡	5	*c*	3.16	0.780	.....	.....

* Resistance range 150 ohms to 4.7 megohms, lead length $1\frac{1}{8}$ in. $\pm \frac{1}{8}$ in.
† Special uninsulated high-voltage type, resistance range 0.27 to 20 megohms.
‡ Radial-lug type.

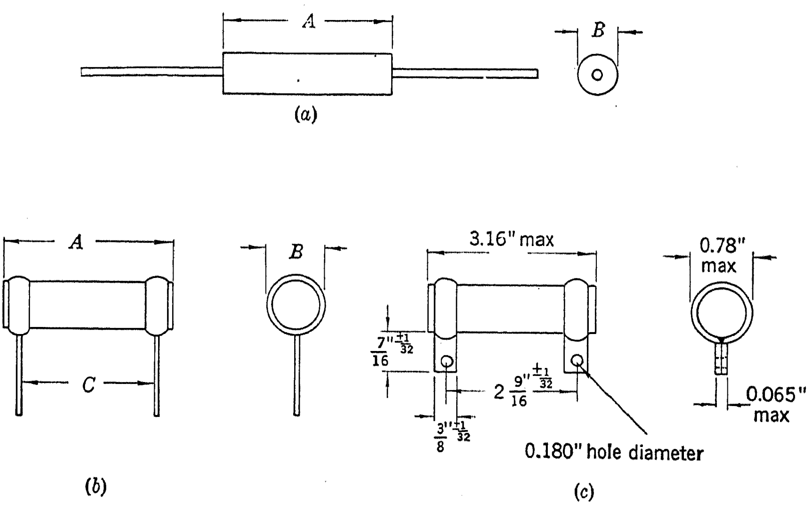


FIG. 2·1.—JAN composition-resistor styles.

cycling, and as to its change of resistance value with temperature, according to Table 2·2.

TABLE 2·2.—JAN COMPOSITION-RESISTOR CHARACTERISTICS
First Letter of Characteristic

Letter	Insulated	Resistant to
A	Insulated	Humidity
B	Insulated	Humidity and immersion
C	Uninsulated	Humidity
D	Uninsulated	Humidity and immersion

Second Letter of Characteristic

Nominal resistance	Maximum allowable per cent change in resistance from 25°C value;			
	at −55°C		at 105°C	
	E	F	E	F
10–1000 ohms	13	6.5	±10	± 5
1100–10k	20	10	±12	± 6
11k–100k	25	13	±15	± 7.5
110k–1M	40	20	±20	±10
1.1M–10M	52	26	±36	±18
11M–100M	70	35	±44	±22

Resistance Value: The next three numbers identify the nominal resistance value. The first two digits are the first two figures of the resistance value in ohms and the third specifies the number of zeros that follow the first two figures.

Resistance Tolerance: The last letter of the symbol designates the symmetrical resistance tolerance; "J" signifies a tolerance of plus or minus 5 per cent maximum; "K," 10 per cent; and "M," 20 per cent.

Color Code.—Since it is hardly practical to put much information on a resistor, and since the component and style are self-evident upon inspection, the resistance value and tolerance are designated by a color code. This code employs bands or dots of color as shown in Fig. 2·2. The use of colored bands around the resistor is general for the insulated types, and the "body, end, and dot" system is usual on the radial-lead uninsulated types. Many charts and other devices are available to help the occasional user to interpret the code, so an explanation is not necessary here. It must be noted, however, that the chart of Fig. 2·2 is incomplete because resistance values lower than 10 ohms are not included

in JAN-R-11. A gold stripe in the third position means that the value given by the first two stripes must be divided by 10; a silver stripe means that the value must be divided by 100. This means that there is a choice of two codes possible for certain values; for instance, a 3-ohm resistor can be coded either orange-black-gold or black-orange-black. From the user's point of view it is decidedly preferable that all resistors between 1 and 10 ohms should use gold in the third position and that all between 0.1 and 1 ohm should use silver, so that the decade into which a resistor value fits can be quickly identified.

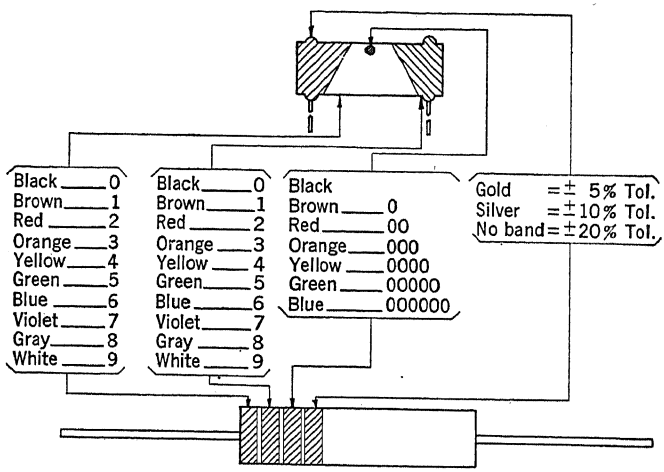


FIG. 2·2.—Standard color code for fixed composition resistors.

It should be noted that in spite of what has been said above about the difficulty of printing numbers on small resistors, International Resistance Company, IRC, uses both the colored stripes and a written identification on many of its units. This is particularly helpful to color-blind individuals, and also in cases where dirt or overheating have made the colors of the bands hard to identify.

2·3. Standard Resistance Values.—Specification JAN-R-11 gives 10 ohms to 20 megohms as the standard range of values of most types of composition resistors. Resistance values outside this range are rarely employed in electronic equipment for use in the field because below 10 ohms wire-wound resistors are usually preferable and because above 20 megohms operation is unreliable due to changes caused by moisture. Some manufacturers make resistors outside their normal ranges on special order.

Preferred-number System.—To limit the production of resistors to a set of standard values that would be adequate for all normal purposes, in 1936 the Radio Manufacturers' Association adopted a preferred-number system for the resistance values of composition resistors. This

system is based upon a logarithmic series, the ratio between each value and the next being approximately the 24th root of 10 (about 1.10). No matter what value is needed at a certain point in a circuit, a standard resistance value can practically always be found within 5 per cent of it. The complete series of standard resistance values from 10 to 100 is as follows:

10 15 22 33 47 68 100	Repeat in next decade.
12 18 27 39 56 82	
11 13 16 20 24 30 36 43 51 62 75 91	

In other decades the same system is used, the number being multiplied or divided by some power of 10. For instance, 3.6 ohms, 56,000 ohms, and 2.7 megohms are all standard Radio Manufacturer's Association values. According to this system, only in ± 5 per cent tolerance are all values to be made; in ± 10 per cent tolerance only the values in the first two lines are to be made, and in ± 20 per cent only those in the first line. Some manufacturers, however, supply 10 and 20 per cent resistors in all the values in the series.

Distribution of Resistance Values within Tolerance Limits.—Many workers, especially scientists, assume that if they buy a considerable number of resistors rated as, for instance, 100 ohms $\pm$ 10 per cent, the distribution of actual measured values will form a normal distribution curve centered on 100 ohms and with the ± 10 per cent points low on the skirts of the curve. This is very far from the truth. The technical difficulties of making resistors to close tolerances and the nature of the sorting processes used by the manufacturers may result in odd-shaped distributions that vary greatly from time to time. For instance, if a large order is filled for resistors of 110 ohms $\pm$ 5 per cent and another for 100 ohms $\pm$ 5 per cent, a purchaser buying 100 ohms $\pm$ 20 per cent shortly afterwards will probably find most of his resistors down around 85 to 95 ohms. It is fairly common to find that a lot of ± 10 per cent resistors has a hole in the center of its distribution curve, units within 5 per cent of the center value being absent or scarce. Since the manufacturers measure every resistor individually, resistance values outside the tolerance limits are not often found.

2·4. Construction of Composition Resistors. *Physical Types.*—General-purpose composition resistors are made in four physical types:

1. Insulated axial-lead resistors. This type of resistor has had by far the most use in equipment in which the Radiation Laboratory has been interested. The resistor element is enclosed in a cylindrical case of insulating material. The leads come out at the centers of the cylinder ends. In this class JAN-R-11 lists seven

styles of resistors, namely RC-10, RC-20, RC-21, RC-30, RC-31, RC-40, and RC-41, and also the new RC-42 style described in the proposed amendment.

2. Uninsulated axial-lead resistors. These resistors are of limited usefulness and are therefore practically obsolete. They have no advantages over insulated styles since they are not made any smaller than insulated resistors of the same wattage rating.
3. Radial-lead resistors. This type has been widely used in the past, but is decreasing in popularity in favor of the insulated axial-lead type. The radial-lead resistor consists of a carbon composition rod with leads attached by winding one around each end of the rod and bringing them out at a right angle to the rod and parallel to each other. They are fastened in place by a process similar to soldering, and then the whole unit, except the ends of the leads, is covered with a protective paint. These resistors are essentially uninsulated. In this class are eight styles of resistors as given in JAN-R-11.
4. Radial-lug resistors. This type is represented by one JAN style (RC-76) and differs from the radial-lead type only in having soldering lugs instead of wire leads. It is seldom used.

Dimensions.—Figure 2·1 shows the dimensions of the various standard styles of resistors. It will be noted that in case of the insulated styles these dimensions are mostly maximum dimensions, and not dimensions that have to be met within certain tolerances. The result is that each style includes resistors of a considerable variety of sizes, ranging from the allowed maximum to about a fourth of the allowed maximum volume. In particular, the half-watt size has been so reduced that the most common size of half-watt resistors is now about $\frac{3}{16}$ by $\frac{3}{8}$ in., which is even smaller than the quarter-watt size given in JAN-R-11.

The standard lead length for all resistors is $1\frac{1}{2}$ in., except for the smallest uninsulated size RC-15, which has leads $1\frac{1}{8}$ in. long. Photographs of some representative types of insulated resistors are shown in Figs. 2·3 to 2·5.

Construction.—The construction of uninsulated resistors is comparatively simple and is practically the same for all companies. It was described in an earlier paragraph of this section. The construction of insulated resistors represents a much more advanced stage of the art, and the problems involved have been met in different ways by the various manufacturers. Two firms, Continental Carbon Company and Ohio Carbon Company, first make up the resistor units in complete form with leads attached, insert them in ceramic tubes, and fill up the ends of the tubes with cement so that the leads project through the cement plugs.

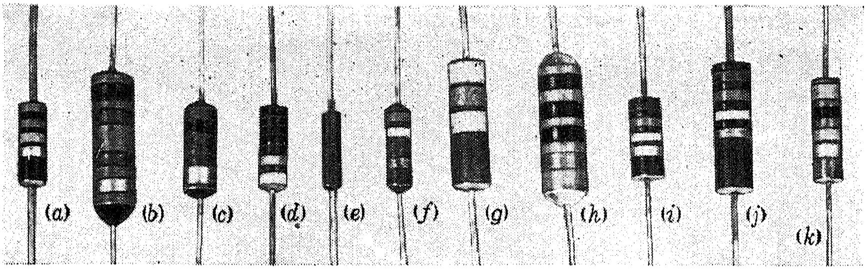


FIG. 2·3.—Typical half-watt insulated resistors: (*a*) Allen-Bradley EB; (*b*) Continental C-½; (*c*) Continental C-⅓; (*d*) Erie 524; (*e*) IRC BTR; (*f*) IRC BTS; (*g*) IRC BT-½; (*h*) Ohio P; (*i*) Speer SI-½; (*j*) Speer SCI-½; (*k*) Stackpole CM-½.

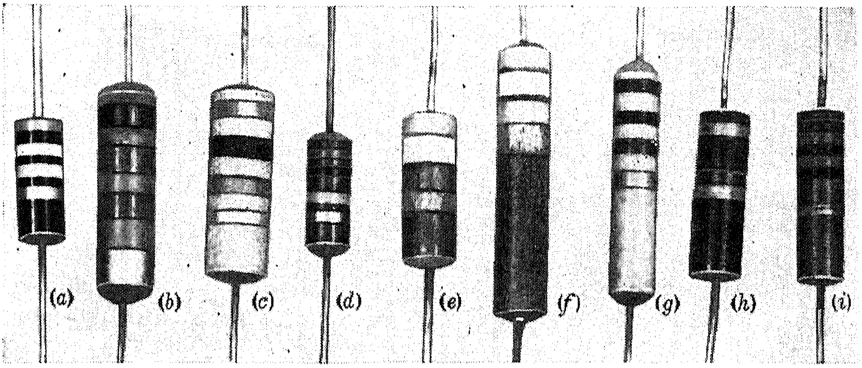


FIG. 2·4.—Typical one-watt insulated resistors: (*a*) Allen-Bradley GB; (*b*) Continental C-1; (*c*) Erie 518 B; (*d*) Erie 525; (*e*) IRC BTA; (*f*) IRC BT-1; (*g*) Ohio PB; (*h*) Speer SI-1; (*i*) Stackpole CM-1.

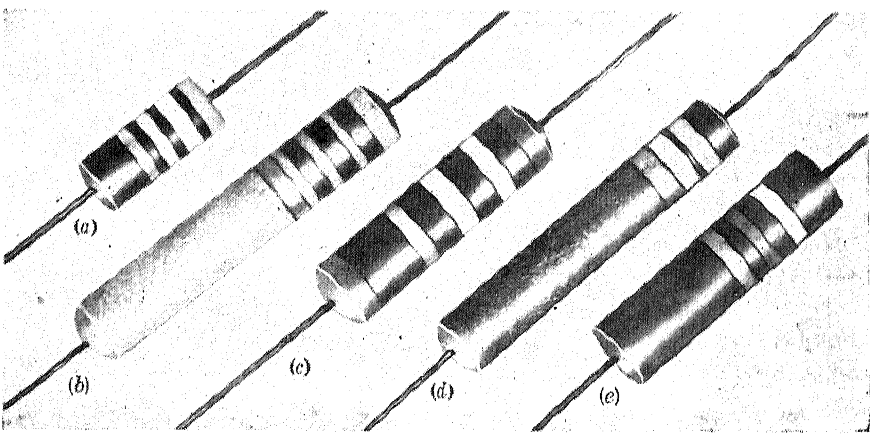


FIG. 2·5.—Typical two-watt insulated resistors: (*a*) Allen-Bradley HB; (*b*) Ohio PFA; (*c*) Erie 526; (*d*) IRC BT-2; (*e*) Speer SI-2.

The leads on the Continental resistors are attached to the carbon resistance element by forming a small flat spiral on the end of the lead wire. The spiral is cemented to the end of the resistance element with a conducting cement. In the Ohio resistors the ends of the carbon element are first coated with a conducting layer; then copper caps, which hold the leads, are forced on. The external appearance of these two makes of resistors is rather similar. In the Ohio resistors the cement in the ends is white; in the Continental resistors it is light brown, the same color as the surface of the ceramic tube itself.

Several manufacturers use thermosetting plastics such as phenol-formaldehyde (Bakelite) as the insulating shell on their carbon resistors. This material has proved to be excellent for this application, giving a high degree of protection against moisture penetration. Allen-Bradley, Erie, Speer, and Stackpole form the resistance element, encase it in phenolic plastic, and imbed the leads, all in one molding operation. The whole resistor becomes one hard solid piece, with no air space between the resistance element and the shell. If it is broken, the break goes smoothly through the black center and the brown casing as if it were all one material. Allen-Bradley, Erie, and Stackpole swage an enlargement on the end of the lead wire. This is inserted into the end of the carbon resistance element, so that after the curing operation the enlarged end of the lead is contained in the interior of the carbon element and cannot be pulled out without breaking the resistor apart. Instead of swaging an enlargement on the end, Speer bends the end back on itself for a short distance and inserts the doubled end in a similar fashion. If the end of a Speer resistor is examined, a small copper-colored spot can usually be seen close to where the lead goes into the resistor. The spot is the end of the doubled-back lead, and its presence is a good way to identify a Speer resistor. One class of Erie resistors is made with brass end caps on the resistance element. This type is molded in Bakelite after the resistance unit is completed.

The International Resistance Company uses a different type of construction from that of other manufacturers, resulting in what is usually called a filament-type resistor. The resistance element consists of a glass tube with carbon composition coated in a thin layer on its outside surface. Each lead has an enlargement shaped something like the hilt of a fencing sword formed on it a little way from the inner end. The leads are pushed into the two ends of the glass tube up to the hilt, so that the ends of the two leads almost meet in the center of the tube. The carbon composition is then coated onto the outside of the tube, the coating covering the two hilts which come up against the tube ends. Finally the unit is molded into a piece of phenolic plastic. The construction helps the heat generated in the resistor to be efficiently removed

by means of the leads, but since the ends of the two leads are fairly close together these resistors may not stand excessive voltages as well as some of the others. The high-frequency performance of this type of resistor is somewhat different from that of the pellet types.

Some of the constructional differences between the various types of insulated resistors can be seen in Fig. 2·6, which shows cross sections and unassembled portions of various resistors.

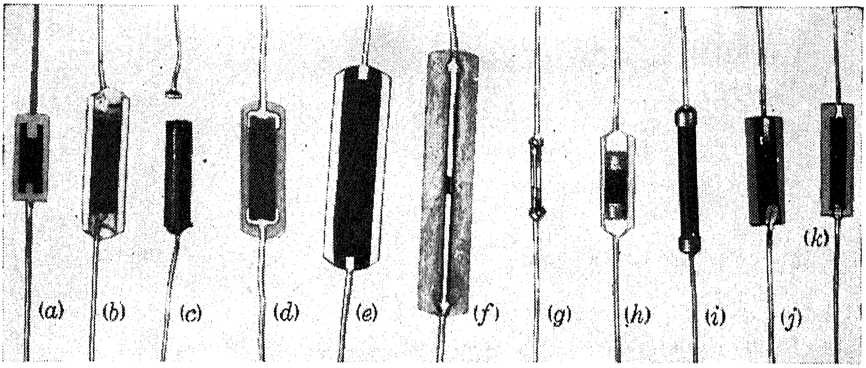


FIG. 2·6.—Internal construction of typical insulated resistors. (*a*) Allen-Bradley (longitudinal section); (*b*) Continental C-1 (longitudinal section); (*c*) Continental C-1 (inside parts); (*d*) Erie 518B (longitudinal section); (*e*) Erie 526 (longitudinal section); (*f*) IRC BT-2 (longitudinal section); (*g*) IRC BT (interior without carbon coating); (*h*) Ohio P (broken open); (*i*) Ohio PB (interior); (*j*) Speer SI-1 (longitudinal section); (*k*) Stackpole CM-1 (longitudinal section).

Body Color.—According to JAN-R-11 the color of an insulated composition resistor can be anything but black, with tan preferred. Uninsulated coaxial-lead resistors are black, the natural color of the carbon resistance unit. Uninsulated radial-lead resistors can be any of many colors, depending on the color-coding system used. The tan color of bakelite-molded insulated resistors is the natural color of the plastic case. Ceramic-insulated resistors are colored tan artifically. Speer resistors differ from most insulated types in being dark brown in color. IRC uses color to distinguish their composition resistors from wire-wound bakelite-molded resistors. The composition resistors (BT) are light-tan in color, and the wire-wound resistors (BW) are dark chocolate brown in color.

2·5. Ratings. *Power Rating.*—The power rating of a resistor is the amount of power it can dissipate for long periods of time without changing seriously in resistance value. Since most composition resistors contain organic binder materials that are unstable when very hot, resistor life depends on temperature of operation. Since temperature of operation depends on the ambient temperature and on the operating temperature rise in the resistor itself, a resistor used in a hot chassis or in a hot climate

must be run at much less than its full rated wattage. Figure 2·7 is a chart from specification JAN-R-11 with Proposed Amendment 1, showing the derating curves of composition resistors. These curves show what per cent of rated wattage can be dissipated in a resistor in open air at any given temperature without serious decrease of resistor life. For instance, if it is expected that the inside of a certain chassis may sometimes reach a temperature of 70°C, a resistor of characteristic BF should be derated to 50 per cent of full power. Thus for an application in which the product of current and voltage is 1.0 watt, a 2-watt resistor would be required.

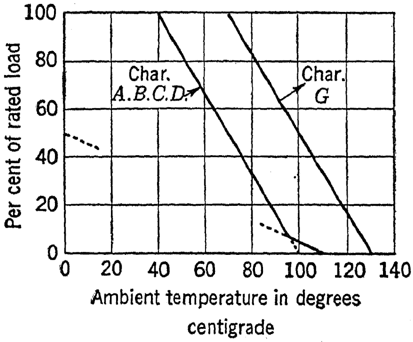


FIG. 2·7.—High-temperature power-derating curves as given in JAN-R-11 with proposed Amendment 1.

According to JAN-R-11 with Proposed Amendment 1, the method of finding whether a resistor meets the wattage rating given by its manufacturer consists of two tests, approximately as follows:

1. Load-life. A group of similar resistors is used for the test. They are connected to terminals and kept in an air chamber at 40°C throughout the test. First the resistance values are measured. Then the direct voltage that should result in dissipation of the rated wattage is applied intermittently, $1\frac{1}{2}$ hr on and $\frac{1}{2}$ hr off, for 500 hr. Four times (at the end of certain off-periods) the resistance values are again measured. The samples are considered to have passed this test if none of the resistors show a change in reading at any time of more than 10 per cent of the initial reading, and if the average maximum change shown by the resistors is not over 6 per cent.
2. High-temperature load-life. The above test is repeated on a fresh group of resistors at an air temperature of 85°C, with lower voltage applied, so that the wattage is derated according to the left-hand derating curve of Fig. 2·7, which is 25 per cent of full wattage at this temperature. The passing requirements are the same as in the load-life test.

In the proposed amendment to JAN-R-11 a new characteristic, "G," was added to the "A, B, C, D" list. A characteristic-G resistor is like a B resistor except that it can be operated at higher temperatures without decrease in life. As shown in Fig. 2·7 a G resistor can dissipate full rated power up to 70°C, at which temperature the others are down to

50 per cent of full rating. This type is useful in equipment that operates in compact hot chassis, especially in the tropics. The tests to see whether a resistor falls in this category are as follows: Load-life under full load at 70°C and high-temperature load-life at 50 per cent of rated wattage at 100°C. So far as is known, Allen-Bradley is the only manufacturer which states that its resistors will fall in this category.

Voltage Rating.—The rated continuous working voltage of a resistor of low or medium resistance is the voltage which makes it dissipate the rated power. It is determined by the formula

$$E = \sqrt{PR},$$

where P is the power rating in watts, after correction for any derating that may be necessary; R is the resistance value in ohms; E is the maximum continuous voltage in volts. If sine-wave alternating current is being applied, E is the rms value.

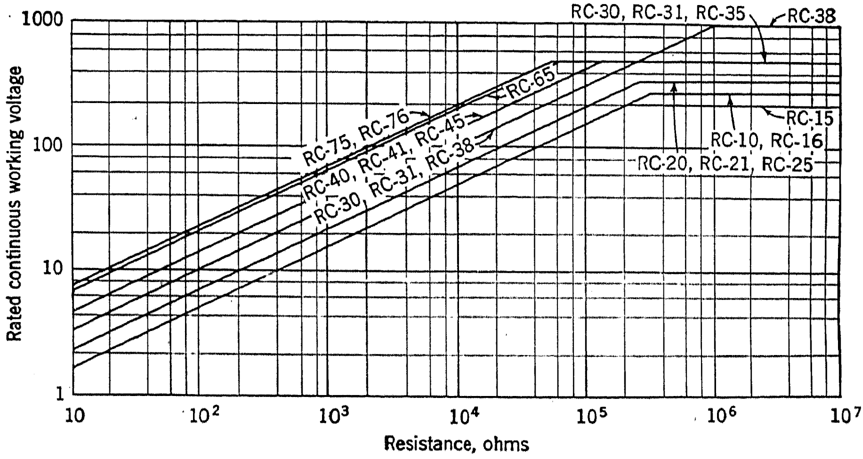


FIG. 2·8.—Rated continuous working-voltage limits of various types of resistors.

In resistors of high resistance little power is dissipated, even with high voltages across the resistor. The upper limit of voltage is set not by the power rating, but by the voltage gradient and the dielectric strength of the materials in the resistor. Figure 2·8 shows the maximum continuous working-voltage ratings of the various types of resistors. The most important maximum ratings are 350 volts for ½-watt resistors and 500 volts for 1- and 2-watt resistors.

When resistors are used under low-duty-cycle pulse conditions, the maximum permissible operating voltage is limited by breakdown rather than by heating. In such applications the peak value of the pulse should not ordinarily exceed 1.4 times the maximum continuous working-voltage

rating for the type used, e.g., 500 volts for an RC-30. Some manufacturers give peak voltage ratings higher than this rule allows, and there are limits as to how far it can be applied. If the pulses are of sufficient duration to raise the resistor temperature excessively, for example, the resistor must be derated even though the interval between pulses may be long enough to make the average heating small. In general the rule must be used with caution if it permits the peak power to be more than about thirty to forty times the normal power rating.

The insulation of an insulated composition resistor is supposed to be good for twice the maximum continuous working-voltage rating for that type of resistor. A resistor is tested by connecting the leads together, laying the unit in a metal V-block about $\frac{1}{16}$ in. shorter than the resistor body, and applying alternating voltage of the appropriate rms value from the leads to the V-block. Certain makes of bakelite-molded resistors, because of thin smears of conducting material on their ends, would sometimes fail in this test if the V-block were longer than the resistor unit. This fact emphasizes the need for the precaution that resistors operating at potentials different from ground should be mounted so that their bodies do not touch grounded metal parts, even though the resistors are called insulated. Sparking around the end of a 1-watt resistor may occur at less than 300 volts if it is mounted in contact with a chassis or bracket.

2·6. Resistance-temperature Characteristics.—The temperature coefficient of resistivity of pure carbon is about -0.04 per cent/°C, and is fairly constant from room temperature to above 100°C. A few types of special-purpose resistors are made of nearly pure carbon and behave about in this way. For general-purpose resistors, however, the words "temperature coefficient" have little useful meaning since plots of resistance against temperature are usually strongly curved. Below room temperature nearly all resistors rise in resistance as temperature is decreased, but above room temperature the resistance may change in either direction, depending on the type and value of the unit. If resistance is plotted against temperature, the curve usually looks like a parabola with its vertex down. The minimum may be anywhere above 15°C and may be at such a high temperature that it does not show at all on a plot covering the resistor's working-temperature range.

The AWS and JAN specifications set limits on the temperature characteristics of resistors in this way: 25°C is considered the reference temperature, and all changes in resistance are computed relative to the value at this temperature. A value for the maximum change in resistance at -55°C is specified, and at intermediate temperatures proportional changes are permitted. The limit is specified in the direction of increased resistance only, because no ordinary composition resistors decrease by

more than a few tenths of a per cent below room temperature. A value for the maximum change at +105°C is specified, with the same proportionality provision, but this time it limits both the increase and decrease of resistance. The limits specified vary with the resistance of the unit, and these limits are given in Fig. 2·9 for both the E-characteristic which has wide limits on temperature changes, and the F-characteristic which permits only half as much change. Figure 2·9 shows the limit lines on a plot of resistance vs. temperature.

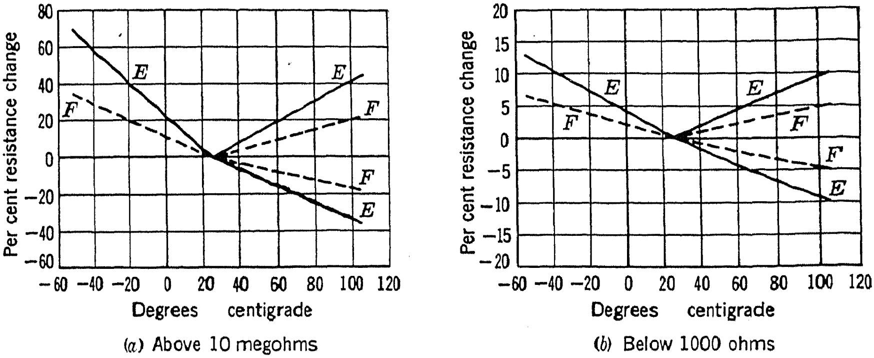


FIG. 2·9.—Maximum resistance change at various temperatures permitted by the standards for highest and lowest ranges of resistor values.

When the effects of temperature on resistance are measured, serious errors can be introduced by humidity variations. In this connection attention should be called to paragraph F-3c in the American War Standard, which says that before this test (and also several others) are carried out, resistors should be "conditioned" by heating at 50°C for 96 hr in a dry oven. Without this conditioning procedure the room-temperature resistance value is so different after the test that the temperature curves are usually distorted and unreliable. Figure 2·10 shows what happened in one such test on a 51,000-ohm resistor. The best conditioning procedure for most accurate testing varies with the make of resistor, and the procedure given in the standard is a compromise.

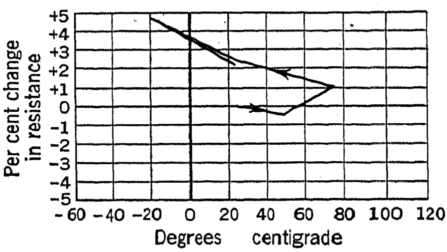


FIG. 2·10.—Changes of an unconditioned resistor with temperature.

Figure 2·11, parts *a*, *b*, *c*, and *d*, shows temperature curves made in the Radiation Laboratory on resistors of several makes. These curves are not reliable data by which to judge the relative quality of different makes of resistors since each curve is based on only five resistors, and it

was found that differences between individual resistors of the same make were often as great as those between the different makes. What the

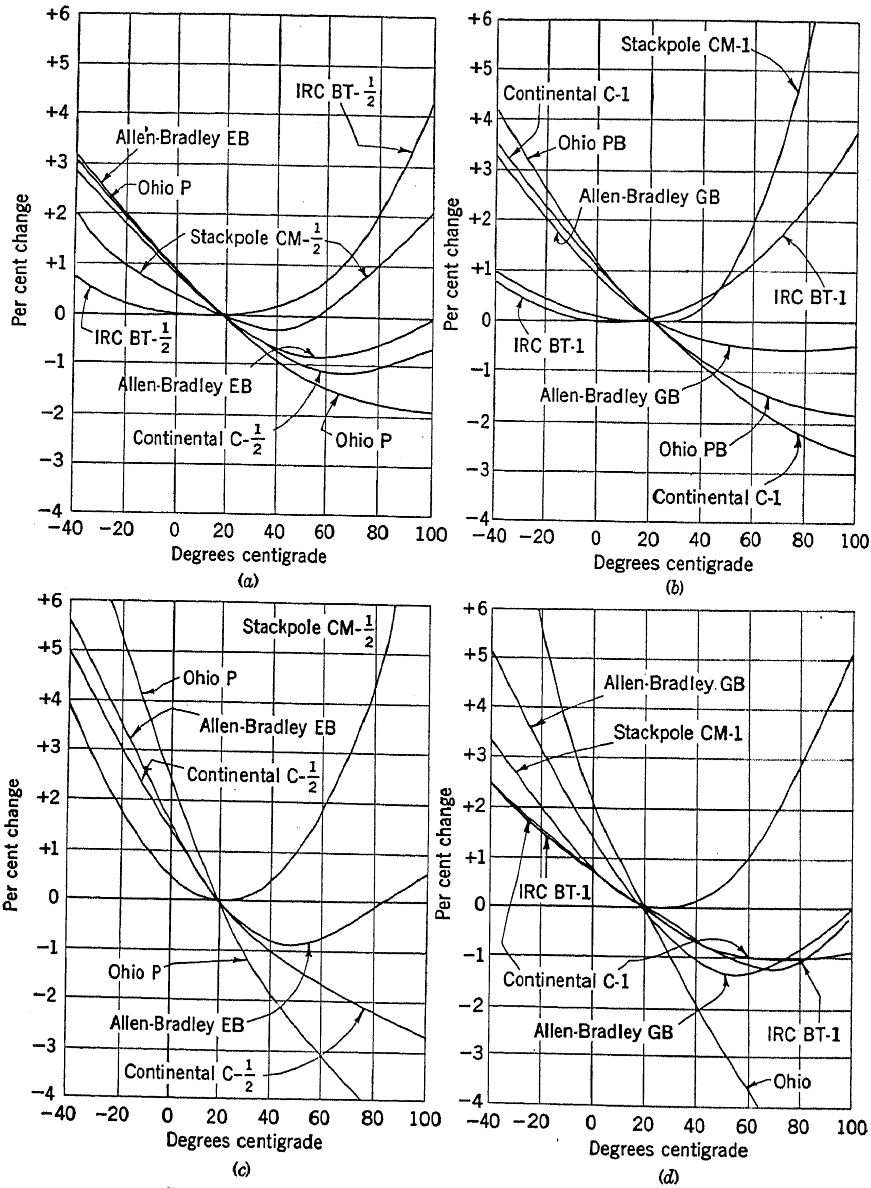


FIG. 2·11.—Resistance-temperature characteristics (1).

curves do show is that great differences are found between different values of the same type and between different wattage types of the same

value. Figure 2·12 shows similar information on more values, based on manufacturers' tests for two types of half-watt resistors. This figure shows that it is extremely unlikely that any single curve can express even roughly the temperature characteristics of a whole line of resistors of the same type.

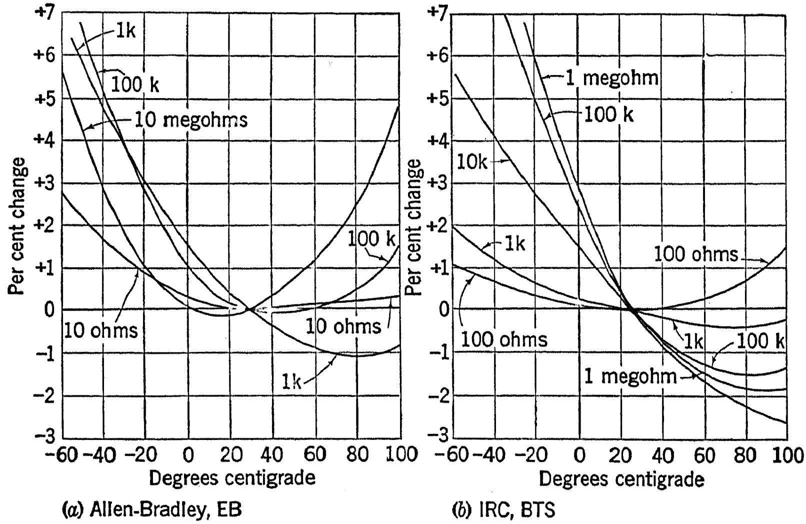


FIG. 2·12.—Resistance-temperature characteristics (2).

Certain materials have very high thermal coefficients of resistance and are useful for various special applications. They are briefly discussed in Sec. 3·12 of the next chapter.

2·7. Noise.—Composition resistors generate noise of two types. The first is the thermal-agitation noise which all resistive impedances generate, ordinarily called "Johnson noise." The voltage generated by a resistor into an open circuit is given by

$$E^2 = 5.50 \times 10^{-23} TR \, \Delta f.$$

E = rms noise voltage.
T = temperature of resistor in degrees absolute.
R = resistance in ohms.
Δf = bandwidth of noise-measuring instrument in cycles per second.

For instance, a 100,000-ohm resistor at 25°C, (298°K) generates 2.68 μv of noise over a bandwidth of 5 kc/sec. This type of noise is of great interest in connection with radar-receiver design, and is covered in detail in Vol. 18 of the Radiation Laboratory Series.

The second type of noise is peculiar to composition resistors and appears when direct current flows through them. The noise voltage is a result of random changes in IR-drop caused by random changes in the

resistance of the unit. The noisiness of a resistor can be expressed in two ways: rms microvolts per volt across the resistor, and relative resistance change in rms parts per million. These two expressions mean the same thing. The noisiness depends, like Johnson noise, on the width of the frequency band passed by the measuring instrument, but in a different manner.

E^2 is proportional to $\log \frac{f_2}{f_1}$.

E = rms noise voltage.

f_2 and f_1 are upper and lower frequency limits of the noise-measuring instrument.

This is the same as saying that for a constant bandwidth—for example, 1 cps—the square of the noise voltage is inversely proportional to the frequency. The original workers in this field[1] determined this law to be true up to 10 kc/sec and work done in the Radiation Laboratory has indicated that it is probably still roughly true in the megacycle region. The noise voltage is nearly, but not exactly, proportional to the direct voltage across the resistor, and for resistors of the same inherent noisiness it is independent of the resistance value. The longer a resistor is, the less noisy it is, if all other factors are equal.

The composition-resistor specifications give as the upper limit of permissible resistor noisiness 3 μv per volt for resistors of $\frac{1}{2}$ watt or less, and 1.2 μv per volt for resistors of more than $\frac{1}{2}$-watt rating. The conditions under which the measurement is to be made are described in American War Standard C75.17-1944 entitled "Method of Noise-Testing Fixed Composition Resistors." These conditions are summarized as follows: The direct voltage applied is the rated continuous-working voltage of the resistor, but never more than 300 volts. The noise-measuring instrument gives maximum response from 400 to 1000 cps, and is 3 db down at about 70 and 5000 cps. The measurement is made by a substitution procedure, by seeing how much 1000-cps signal from a standard signal generator is required to make the noise meter read the same as it did with the resistor connected. Noise measurements are not required on resistors below 1000 ohms.

It is of interest to compare the amounts of the two kinds of noise generated by a resistor under various conditions. Figure 2·13 shows noise, in rms microvolts per kilocycle per second, as a function of frequency, for two values of resistance, without and with direct voltage applied. The horizontal lines show that Johnson noise is independent of frequency. The sloping lines are noise-voltage estimates for resistors

[1] C. J. Christensen and G. L. Pearson, "Spontaneous Fluctuations in Carbon Microphones and Other Granular Resistances," *Bell Sys. Tech. J.*, **15**, 197, (April 1936).

that just meet the $\frac{1}{2}$-watt specification (3 μv per volt) when measured with a noise meter of frequency limits from 70 to 5000 cps. It will be seen that at 1000 cps the carbon-noise voltage of a 100,000-ohm resistor with 100 volts across it is about 100 times as great as the Johnson-noise voltage and completely covers it. At frequencies higher than about 10 Mc/sec, however, the Johnson noise becomes the more important of the two. The same situation exists in a 1000-ohm resistor with 10 volts across it. For this and other reasons carbon noise is of little interest in

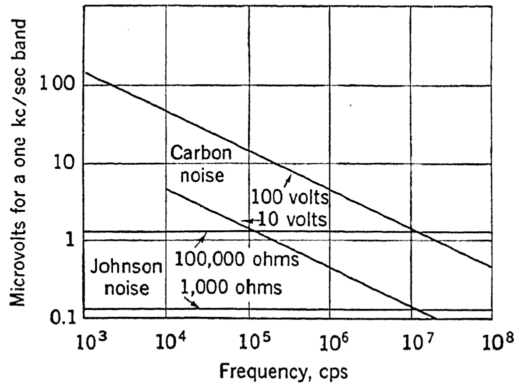


FIG. 2·13.—Resistor noise.

radar equipment where high-gain amplifiers generally work well above 10 Mc/sec.

2·8. High-frequency Properties. *Theory.*—In order to use composition resistors properly at high frequencies it is necessary to know how their properties differ in this region from their direct-current properties. The frequency range of chief interest here is from 1 to approximately 100 Mc/sec, where radar intermediate-frequency amplifiers operate. The characteristics which must be considered are:

1. Direct end-to-end capacitance.
2. Total capacitance.
3. Change in resistance with frequency.
4. Inductance.

Direct end-to-end capacitance is of interest where a high-frequency signal is being fed through a resistor to a point not grounded for signal frequency, as in an attenuator or a feedback amplifier. Total capacitance is of interest where one end is grounded for signal frequency, and current through the resistor causes a signal voltage to appear at the other end, as in the plate-load resistor of an amplifier. Change of resistance with frequency is of interest in some amplifiers and in certain measuring

methods. The inductance of composition resistors does not often cause trouble below 100 Mc/sec except where very low values of resistance are used, as in the shunt resistors of attenuators.

There is no simple equivalent circuit with constant lumped parameters that will duplicate the changes of impedance with frequency of a composition resistor. For many purposes the circuit of Fig. 2·14 is sufficient, where R_p (the "parallel resistance") is the reciprocal of the conductance, and C_t is the total capacitance. In radar-receiver design work this circuit is generally used and it is assumed that R_p is equal to the d-c resistance. At higher resistances and higher frequencies the values of R_p and C_t both decrease markedly as compared with their low-frequency values. It has been thought that this effect is caused by the granularity of the material used in the carbon-pellet-type resistors—that the individual conducting grains have capacitance to each other which at high frequencies shunts out some of the resistance, as shown in Fig. 2·15.

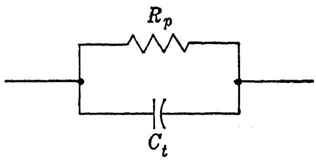


FIG. 2·14.—Simple equivalent circuit of a resistor.

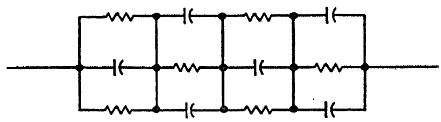


FIG. 2·15.—Equivalent circuit of a granular resistor.

G. W. O. Howe[1] has shown, however, that it is unnecessary to assume granularity to account for this effect; that because of its distributed capacitance, even a completely homogeneous resistor should decrease in parallel resistance and in capacitance as the frequency increases. He defines distributed capacitance as the effective capacitance (that is, the charge divided by the potential difference) of a given small part of the length of a resistor to the corresponding part in the other half of the resistor. He then shows that without serious error the distributed capacitance can be assumed equal along the length of the resistor, and calculates its value per centimeter for several ratios of length to diameter of a simple unenclosed resistance pellet. This can be considered to be a short-circuited transmission line half as long as the resistor, (see Fig. 2·16*b*) and its sending-end impedance may be calculated as a function of its length, l (cm); its distributed capacitance, C ($\mu\mu$f per cm); the total d-c resistance R of the resistor; and the frequency f (cps). The result is a pair of curves (Fig. 2·17) showing how the resistance and capacitance decrease as the product $flCR$ increases. The fact that the d-c resistance and the frequency appear in the horizontal coordinate of this curve suggests that the product of these two quantities may be a good horizontal

[1] G. W. O. Howe, *Wireless Engineer*, **12**, 291 (1935); **12**, 413 (1935); **17**, 471 (1940).

scale to use when plotting measured values of high-frequency resistance or capacitance of a resistor. It has been found that with carbon-pellet resistors this works so well that a single curve shows the ratio of r-f to d-c resistance for most values of resistance and frequency being considered,

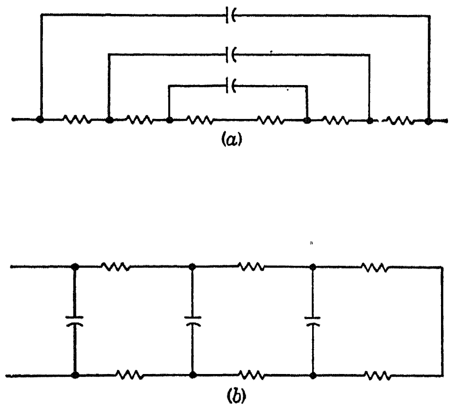


FIG. 2·16.—Equivalent circuit assumed by G. W. O. Howe.

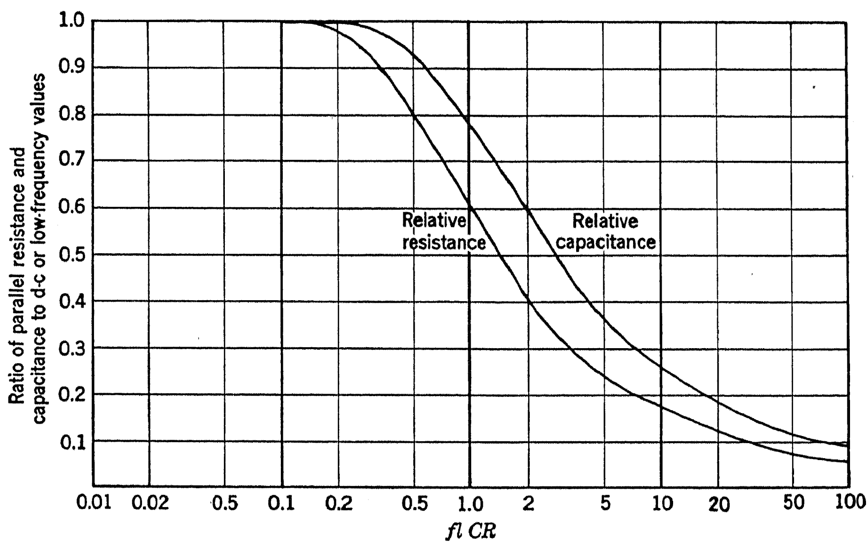


FIG. 2·17.—G. W. O. Howe's theoretical resistance and capacitance curve.

and this curve looks a good deal like Howe's curve. For compactness we shall call this condition the "resistance-frequency product" law.

For filament-type resistors such as the IRC BT styles, this theory does not tell the whole story. In these resistors the leads project inside the tube on which the composition is coated, and their ends are fairly close together. This has two effects: it increases somewhat the capac-

itance between the leads, and it gives considerable capacitance between a lead and the portion of the resistor which is separated from it by only a thin layer of glass. This has the effect that at low frequencies the total capacitance of the unit is increased, and at high frequencies all except the central part of the resistor is partly short-circuited by its capacitance to the leads. The ratio of length to diameter of these resistors is greater than that of the carbon-pellet types, a property which, according to Howe's theory, is supposed to move the relative-resistance curve to higher frequency values. In these resistors, therefore, most of the resistance change with frequency is caused by the lead arrangement. This is confirmed by the fact that IRC Type-F and Type-MPM resistors (which are much like the BT styles in construction of the resistance unit but which do not have leads projecting into their interior) show much smaller resistance changes at high frequencies than the BT styles. In these types, in fact, there is evidence to indicate that as frequency increases, resistance increases a few per cent above the d-c value at first, then falls below the d-c value, and finally rises above it once more.

Methods of Measurement.—Four general types of methods have been used for measuring high-frequency properties of resistors. In the low-resistance ranges, below 1000 ohms, methods that give the resistance and reactance in terms of an equivalent series circuit are generally used. Above 1000 ohms or so, parallel methods are more satisfactory. In any case, it is usual to express the impedance in parallel-circuit form except for resistors below about 50 ohms, where inductance begins to become appreciable.

The first method is the use of a radio-frequency bridge. The General Radio 821-A Twin-T Impedance-measuring Circuit is suitable in the frequency range from 1 to 30 Mc/sec for resistors over 1000 ohms. It reads directly in conductance and parallel capacitance. The second method is the use of a Q-meter or similar circuit, with either a series connection for low resistances or a parallel connection for high resistances. In the parallel connection, the capacitance can be read directly and the resistance is calculated by a formula given in the meter instruction book. Resistance readings are not precise because small differences between large meter readings are often involved, but capacitance readings are satisfactory. The third method is the use of a voltage-divider circuit similar to that of Fig. 2·18. In this method the resonant circuit is tuned so that output is minimum, the unknown resistor is attached, the resonant circuit is retuned, and the output is read again. Direct end-to-end capacitance is given by the change in the condenser setting. Resistance is calculated from the measured input and output voltages with and without the resistor, and the known resistance in the lower half of the divider. This resistor is chosen low enough to permit the assumption

that its r-f resistance is equal to its d-c value. This method has been successfully used at 60 Mc/sec.

The fourth method uses what might be called a "multiplied-substitution" principle. A circuit is set up containing a meter, and having at least two places where resistors can be inserted, such that a known low resistor in one position loads the circuit and decreases the meter reading just as much as a resistor that is higher by a known factor in the other position. One such circuit is that of Boella,[1] shown in Fig. 2·19.

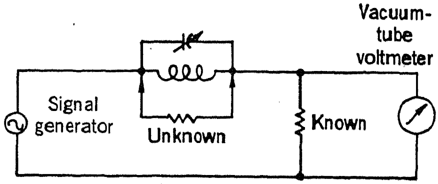


FIG. 2·18.—Voltage-divider circuit.

In the circuit of Fig. 2·19 if

$$R_1 \gg \frac{1}{\omega C_2},$$

then

$$R_2 = R_1 \left(1 + \frac{C_2}{C_1}\right)^2.$$

The variable capacitor is tuned for a maximum reading for each adjustment of the switches. Another such arrangement, used by Miller and

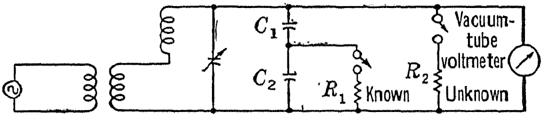


FIG. 2·19.—Boella's capacitance-divider circuit.

Salzberg, uses a transmission line that is much shorter than a quarter wavelength, short-circuited at one end and tuned with a variable capacitor at the other end.[2] The method makes use of the fact that the voltage varies nearly linearly along the line so that a low resistor across the line near the short-circuited end will load the line as much as a higher resistor farther from the short-circuited end. This method was used up to 250 Mc/sec.

When capacitance measurements are made, the method of mounting the resistor on the measuring instrument has such a great effect on the result that reported values of capacitance are almost meaningless unless the method of mounting is described. A resistor under test can be con-

[1] M. Boella, *Alta Frequenza*, **3**, No. 2 (April 1934).
O. S. Puckle, *WE*, **12**, 303 (1935).

[2] J. H. Miller and B. Salzberg, *RCA Review*, **3**, 486 (Reissued as *RCA Publication St*-153).

sidered a network of capacitances, where C_d is the direct end-to-end capacitance and C_a and C_b are the capacitances to ground of the two leads. The total capacitance is $C_a + C_d$, for when this value is measured one end is grounded. The value of C_d is affected mainly by the nearness of the resistor to the chassis since grounded conductors near the side of the resistor will distort its field. The distance from resistor to chassis should be at least as great as the minimum distance between the leads or end caps of the resistor unit. Total capacitance is greatly affected by lead length on the ungrounded side of the resistor. Whenever total capacitance is being measured for a given circuit application, the resistor must be mounted as nearly as possible as it is to be mounted in use. If total capacitance is being measured for research or comparison, the leads should preferably be straight and the exposed lead lengths should be stated. It is possible to mount some resistors in such a way that C_a practically disappears and the total capacitance becomes about the same as the end-to-end capacitance C_d.

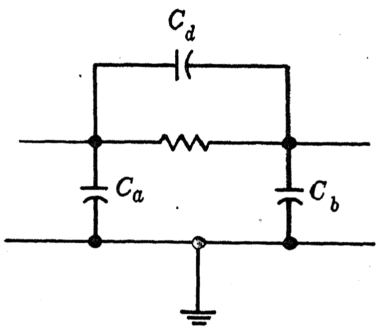


FIG. 2·20.—Equivalent circuit including ground capacitances.

High-frequency Properties of Certain Resistors.—The results of some measurements of the high-frequency properties of resistors are given here in tables and curves. This information is incomplete since much of the original work was done before some of the present types of resistors appeared on the market, and often measurements were made only on types that happened to be easy to obtain. For uniformity the results are given as the ratio of r-f parallel resistance to d-c resistance plotted against the resistance-frequency product, even though the product law is not followed in all cases.

Figure 2·21 shows some curves received from a source outside the Radiation Laboratory. Measurements were made mainly by the bridge method below 30 Mc/sec. The number of samples tested and the scatter of the measured points are not known. Figure 2·22 from data by Drake[1] shows the resistance-frequency characteristics of two 1-watt resistor types. Each curve is based on 14 samples, three to five twin-T bridge measurements being made on each, in the range from 1 to 30 Mc/sec. The resistance values are from 4000 ohms to 5 megohms. The rms deviations of the points from the curves are 3.5 per cent of the d-c resistance for the International Resistance Company curve, and 2.5 per

[1] D. T. Drake, "High-frequency Characteristics of Resistors," RL Report No. 520, March 1944.

cent for the Allen-Bradley curve. The original data showed the curves of the individual resistors following closely the form of the average curve,

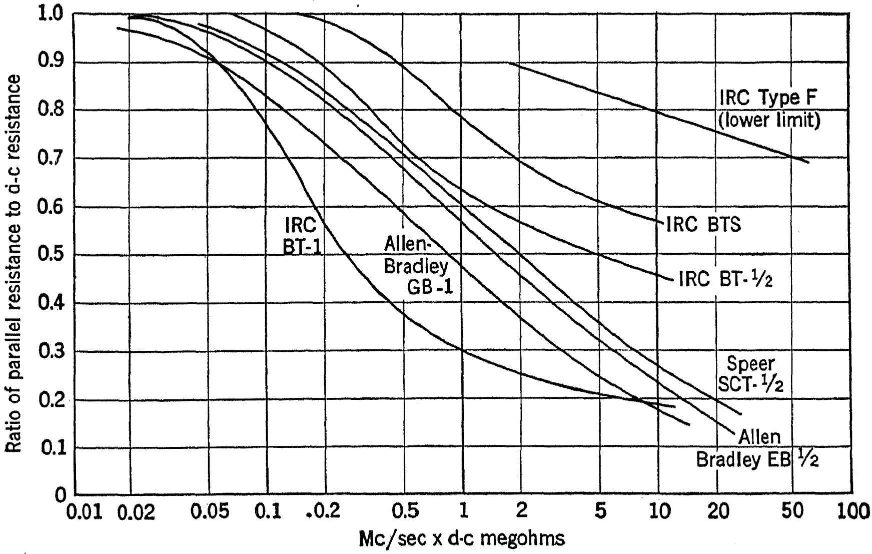


FIG. 2·21.—Resistance-frequency characteristics (1).

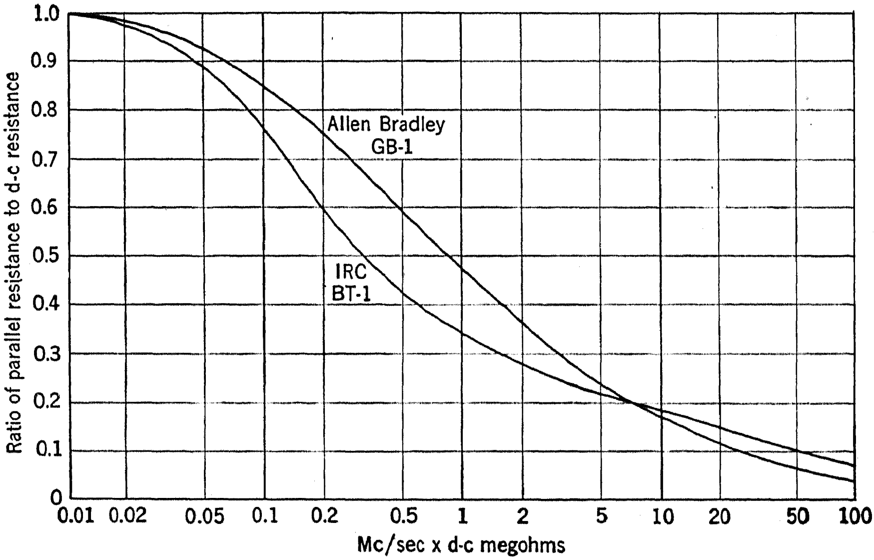


FIG. 2·22.—Resistance-frequency characteristics (2).

indicating that the product law was valid for these resistors and frequencies. Figure 2·23 shows curves of 50,000-ohm resistors of several types and wattages, based on bridge measurements made in the Radiation

Laboratory at 3, 10, and 30 Mc/sec. Three samples were measured to obtain each point.

Table 2·3, from measurements by H. Beveridge at the Naval Research Laboratory, shows the direct end-to-end capacitance, the total capacitance, and the decrease in resistance from d-c to r-f for 18 composition-resistor types. All measurements were made at 60 Mc/sec on resistors of 2000-ohm and 10,000-ohm resistance. Each figure given is based on three samples. Measurements of end-to-end capacitance and of parallel resistance were made by the voltage-divider method. The instruments were calibrated by assuming that the IRC Type-MPM resistors had the same resistance at 60 Mc/sec as at d-c. There is some evidence that the 10,000-ohm MPM units may be a few per cent higher at this frequency than at d-c. This would affect the resistance-decrease figures given for the other resistors of this value. During the total-capacitance measurements the units were parallel to ground and $\frac{1}{4}$ in. to $\frac{1}{2}$ in. above it, depending on size. The exposed lead length, on the ungrounded end, was in each case about half the length of the resistor body.

Figure 2·24 shows some results of measurements by Miller and Salzberg on IRC Type-F 1-watt resistors.[1] As the figure shows, these units do not follow the product law, so a separate curve is

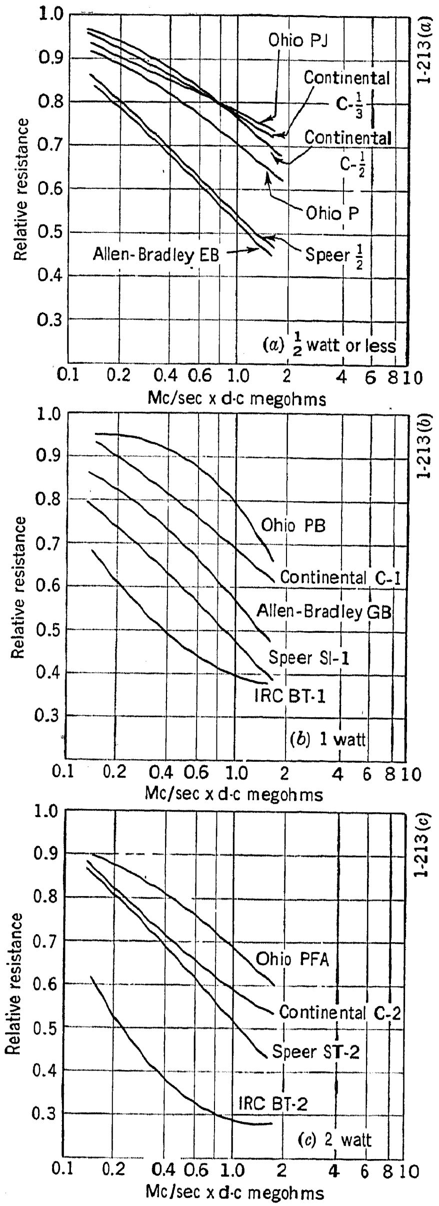


Fig. 2·23.—Resistance-frequency characteristics (3).

used for each resistance value. The measurements were made at fre-

[1] J. H. Miller and B. Salzberg, ibid.

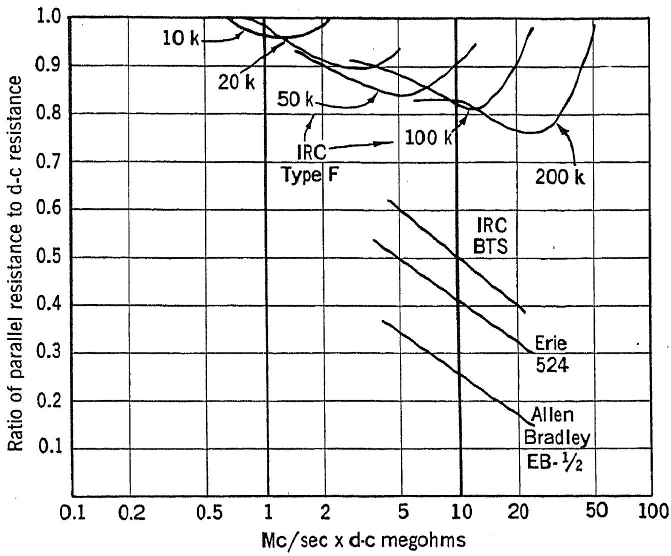


FIG. 2·24.—Resistance-frequency characteristics (4).

TABLE 2·3.—RESISTOR CHARACTERISTICS AT 60 MC/SEC

Maker	Type	Watts	2000 ohms			10,000 ohms		
			*A**	*B*†	*C*‡	*A**	*B*†	*C*‡
IRC	MPM	¼		0.01	0.25		0.02	0.25
Globar	997-A	⅛	5.3	0.25	0.37	27.0	0.27	0.38
IRC	BTR	⅓	3.1	0.28	0.42	18.8	0.20	0.40
IRC	BTS	½	2.5	0.24	0.40	18.5	0.20	0.35
Erie	524	½	0.33	0.11	0.35	12.4	0.14	0.30
Allen-Bradley	EB	½	4.7	0.30	0.50	27.0	0.26	0.45
Stackpole	CM-⅓	⅓	0.30	0.16	0.35	9.6	0.14	0.30
Speer	SI-½	½	4.8	0.25	0.45	29.3	0.29	0.45
Stackpole	CM-½	½	0.85	0.12	0.45	9.3	0.09	0.30
Erie	504B	½	6.2	0.40	0.75	25.2	0.23	0.60
Erie	525	1				22.4	0.33	0.65
Allen-Bradley	GB	1	8.1	0.38	0.75	33.4	0.34	0.73
IRC	BT-½	½	3.5	0.23	0.55	17.3	0.19	0.50
Speer	SCI-½	½	2.7	0.21	0.58	10.8	0.10	0.50
Stackpole	CM-1	1	0.90	0.10	0.55	8.8	0.08	0.52
IRC	BTA	1	7.4	0.42	0.85	27.0	0.26	0.68
Erie	518B	1	4.2	0.34	0.90	16.4	0.21	0.90
IRC	BT-1	1	19.8	0.7+	1.40	58.3	0.46	1.10

* A Percentage decrease in resistance at 60 Mc/sec.
† *B* End-to-end capacitance in micromicrofarads.
‡ *C* Total capacitance in micromicrofarads.

quencies from 30 to 250 Mc/sec by the transmission-line method previously mentioned. Some Q-meter measurements, done mostly at IRC, and a few at Radiation Laboratory, indicate that IRC Types-F and -MPM resistors apparently have higher resistance in the neighborhood of 10 Mc/sec than at d-c.[1] The increase found was about 5 to 10 per cent. The lower resistance values measured (around 10,000 ohms) stayed above their d-c resistance up to 30 Mc/sec or higher, depending on wattage and type.

Figure 2·24 also shows the results of measurements made with a high-frequency Q-meter on resistors of 100,000 to 300,000 ohms at frequencies from 30 to 120 Mc/sec. In this frequency range the resistance-frequency product law begins to fail, and the failure is relatively worse for resistors whose values are fairly close to their d-c values (i.e., those with curves in the upper part of the figure). The curves of this figure should therefore be considered as very rough, and the information should not be used at other frequencies.

Figure 2·25 shows Drake's total-capacitance measurements for the resistors of Fig. 2·22. Points are given instead of smoothed curves in order to show the great variability of capacitance between resistors. The decrease in capacitance with increasing frequency can be accounted for by Howe's theory.

In certain high-frequency circuits the use of coils wound on resistors and connected across them is common practice. If such a coil must have a uniform or high inductance value or a high Q, a resistor with metal end caps should not be used. Since large currents are induced in the end caps, they decrease the inductance of the coil and increase its losses.

2·9. Stability.—In some measuring applications where great accuracy is not needed, composition resistors are used as parts of high-resistance voltage dividers, etc. For such applications it is of interest to know what changes in value may take place in a resistor that is kept indoors and used only occasionally, and then at only a small fraction of its rated wattage in a cool instrument.

Little investigation has been carried out on this subject. Available data indicate that what changes take place are mainly caused by humidity variations. Moisture can diffuse in and out of even the most completely protected general-purpose resistors, but it may take weeks for it to do so. In general, a resistor in equilibrium with a moderately humid atmosphere is likely to have a higher resistance value than the same unit in equilibrium with a dry atmosphere. The amount of change varies with the make and value of the unit, but its maximum change for the makes on which information is available is in the neighborhood of 3 per cent for conditions ordinarily found in laboratories in the northern United States.

[1] E. E. Johnson, "F-Type Resistors," *IRC Report* 237, July 1945.

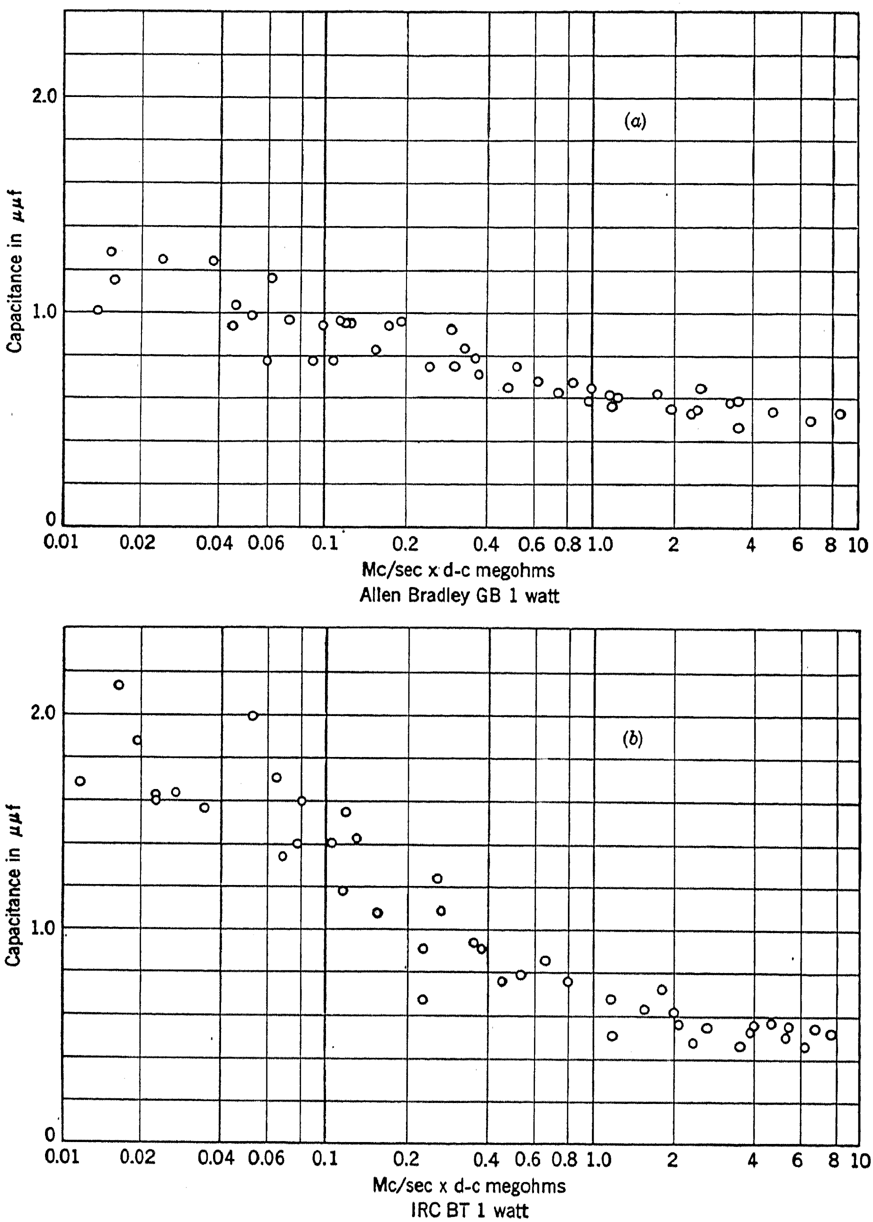


FIG. 2·25.—Total capacitance-frequency characteristics.

A resistor that is used under load or in a hot chassis generally dries out fairly soon, and if it is used very often stays fairly dry. In such cases changes in resistance are caused by high temperature rather than by humidity.

The humidity test given in the AWS and JAN specifications is 250 hr at 95 per cent relative humidity at a temperature of 40°C. Before this test is run, resistors should have been conditioned as for a temperature test. The permissible resistance change is 10 per cent. The change that takes place in this test is generally an increase in resistance. As was mentioned before, resistors in molded-bakelite cases ordinarily endure humidity tests better than those with ceramic cases.

The changes that take place when a resistor is operated for a long time at or near rated load can often be attributed to the decomposition, under the influence of high temperatures, of the organic binder mixed with the carbon. Since this results in the formation of carbon, a decrease in resistance would be expected. In the carbon-pellet resistor types decreases in resistance value are usually found, but in the filament types the change is more likely to be an increase.

The standard load-life tests have already been described in Sec. 2·5. The fact that these tests cover a fairly short time, (three weeks according to JAN-R-11 with proposed amendment 1, and six weeks according to AWS C75.7-1943) and the fact that the permissible changes are fairly large show that this test is not particularly severe. The wattage ratings determined by these tests are not conservative and consequently temperature deratings should be carefully observed wherever long-period reliability is important.

The standard overload test is the application of $2\frac{1}{2}$ times the rated continuous-working voltage for a period of 5 sec up to certain limits. To pass this test, resistors must remain within 5 per cent of their orginal values.

Most composition resistors change somewhat in value when they are soldered to connecting terminals. Joint Army-Navy Specification R-11 specifies that this change must be less than 3 per cent under a certain soldering test.

The mechanical strength of a composition resistor is adequate for nearly all applications. A 5-hr vibration test is specified, which resistors must withstand without showing mechanical damage or changing in value more than 1 per cent. For all types except the small uninsulated RC-15 the leads must be able to withstand a pull of 5 lb and a twisting test.

Two types of cyclic temperature tests are specified. The first involves five cycles in air, starting at room temperature and alternating between $-55°$ and $+85°$C. This cyclic treatment shall not cause a resistance

change of more than 5 per cent for any one resistor, and 90 per cent of a sample group shall have changed less than 2 per cent.

The second cyclic test is the salt-water immersion test, which determines the first of the two "characteristic" letters in a resistor's code designation. Each cycle lasts 3 hr: 1 hr in saturated salt water at 100°C, 1 hr in salt water at 0°C, and 1 hr of operation at maximum rated voltage in air at 40°C. After nine such cycles, a resistor must have changed not more than 10 per cent to qualify for Characteristic *B* or *D*. This is a very severe test, and for most purposes resistors that will not pass it (Characteristics *A* or *C*) are perfectly satisfactory. Most bakelite-insulated resistors will pass the test; most ceramic-cased resistors will not pass; and very few uninsulated resistors of any type will pass.

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CHAPTER 3

FIXED WIRE-WOUND AND MISCELLANEOUS RESISTORS

BY M. D. FAGEN AND G. EHRENFRIED

This chapter consists of three main divisions, the first being devoted to standard wire-wound resistors capable of dissipating appreciable amounts of power, the second to low-power wire-wound resistors of relatively high accuracy and stability, and the third to a number of miscellaneous types of resistors that are of interest for various special applications.

POWER-TYPE WIRE-WOUND RESISTORS

3·1. Standard Types.—The units to be discussed in Secs. 3·1 through 3·5 are those covered by the joint Army-Navy specifications JAN-R-26, "Resistors, Fixed Wire-wound, Power Type" and JAN-R-184, "Resistors, Fixed, Wire-wound (Low Power)." The latter are similar to the molded axial-lead insulated composition resistors previously discussed. They are made in $\frac{1}{2}$-, 1-, and 2-watt ratings, in both 5 and 10 per cent tolerances. Their dimensions and resistance ranges are given in Table 3·1 and Fig. 3·1.

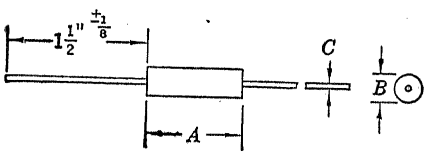

FIG. 3·1.—Low-power wire-wound resistor dimensions.

TABLE 3·1.—LOW-POWER FIXED WIRE-WOUND RESISTORS*

Type	Watts	Dimensions			Resistance, ohms	
		A, max., in.	*B*, max., in.	*C*, min., in.	min.	max.
RU-3	$\frac{1}{2}$	$\frac{21}{32}$	$\frac{15}{64}$	0.032 (No. 20 A.W.G.)	0.24	470
RU-4	1	$1\frac{9}{32}$	$\frac{9}{32}$	0.036 (No. 19 A.W.G.)	0.51	2200
RU-6	2	$1\frac{25}{32}$	$\frac{11}{32}$	0.036 (No. 19 A.W.G.)	1.0	3300

* These resistors are specified by JAN-R-184. They are identical in appearance with insulated composition resistors except that the first band of the color code is twice normal width to identify the units as wire-wound.

The JAN-standard power-type resistors are made in 35 styles, and may be classified into six groups: ferrule-, stack-mounting-, tab-, screw-, axial-tab-, and axial-wire-lead-terminal resistors. Their dimensions and resistance ranges are given in Table 3·2 and Fig. 3·2. Figure 3·3 shows a group of typical power-type resistors.

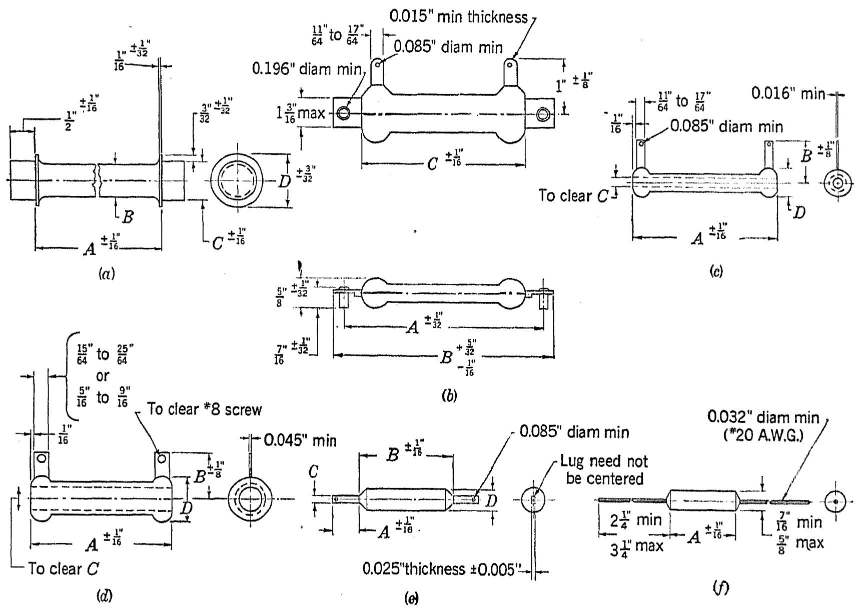

FIG. 3·2.—Power-type resistor dimensions.

The type designations used for power-type resistors are similar to those for composition resistors, consisting of three letters and five numbers as follows:

RW 10 F 100

Component | Style | Characteristic | Resistance

Component: RW identifies the unit as a power-type wire-wound resistor.

Style: The first two figures identify the size and shape of the unit as explained in Table 3·2.

Characteristic: The third letter identifies the class and grade of the unit according to Table 3·3.

Resistance: The next two numbers give the first two significant figures, and the last number gives the number of zero following these figures, the combination expressing the resistance in ohms. For

TABLE 3·2.—POWER-TYPE FIXED WIRE-WOUND RESISTORS

	JAN type	Dissipation rating, watts			Maximum* resistance kilohms	Dimensions, in.			
		Class I	Class III	Class II		A	B	C	D
Ferrule terminals Fig. 3·2*a*	RW-10	140	80	40	63	$10\frac{7}{16}$	1 to $1\frac{5}{16}$	$1\frac{1}{8}$	$1\frac{5}{16}$
	RW-11	120	67	37	63	$8\frac{5}{8}$	1 to $1\frac{5}{16}$	$1\frac{1}{8}$	$1\frac{5}{16}$
	RW-12	90	50	25	50	$6\frac{7}{16}$	1 to $1\frac{5}{16}$	$1\frac{1}{8}$	$1\frac{5}{16}$
	RW-13	50	27	15	25	$4\frac{1}{8}$	$\frac{11}{16}$ to $1\frac{1}{16}$	$\frac{13}{16}$	1
	RW-14	40	22	12	16	$3\frac{7}{16}$	$\frac{11}{16}$ to $1\frac{1}{16}$	$\frac{13}{16}$	1
	RW-15	20	11	6	6.3	$1\frac{15}{16}$	$\frac{7}{16}$ to $\frac{3}{4}$	$\frac{9}{16}$	$\frac{3}{4}$
	RW-16	15	8	4	4	$1\frac{3}{8}$	$\frac{7}{16}$ to $\frac{3}{4}$	$\frac{9}{16}$	$\frac{3}{4}$
Stack-mounting terminals Fig. 3·2*b*	RW-20	22	13	6	2	2	$2\frac{1}{2}$	$1\frac{1}{4}$	....
	RW-21	31	17	8	5	$2\frac{3}{4}$	$3\frac{1}{4}$	2	....
	RW-22	48	29	14	10	$4\frac{1}{4}$	$4\frac{3}{4}$	$3\frac{1}{2}$	....
	RW-23	60	34	17	16	$5\frac{1}{2}$	6	$4\frac{3}{4}$	....
	RW-24	70	35	19	20	$6\frac{3}{4}$	$7\frac{1}{4}$	6	....
Tab terminals Fig. 3·2*c*	RW-30	7	3	2	1	1	$\frac{7}{8}$	0.140	$\frac{19}{32}$ max.
	RW-31	8	4	3	2	$1\frac{1}{2}$	$\frac{7}{8}$	0.140	$\frac{19}{32}$ max.
	RW-32	16	8	5	4	2	$\frac{7}{8}$	0.140	$\frac{19}{32}$ max.
	RW-33	24	12	8	16	3	$\frac{7}{8}$	0.140	$\frac{19}{32}$ max.
	RW-34	30	15	9	16	3	$\frac{15}{16}$	0.470	$\frac{29}{32}$ max.
	RW-35	38	20	12	20	4	$\frac{15}{16}$	0.470	$\frac{29}{32}$ max.
	RW-36	60	33	18	40	4	$1\frac{7}{32}$	0.690	$1\frac{5}{16}$ max.
	RW-37	78	45	22	50	6	$1\frac{7}{32}$	0.690	$1\frac{5}{16}$ max.
	RW-38	100	57	30	80	8	$1\frac{7}{32}$	0.690	$1\frac{5}{16}$ max.
	RW-39	155	86	43	100	12	$1\frac{7}{32}$	0.690	$1\frac{5}{16}$ max.
Screw terminals Fig. 3·2*d*	RW-40	30	15	9	16	3	$\frac{31}{32}$	0.470	$\frac{29}{32}$ max.
	RW-41	38	20	12	16	4	$\frac{31}{32}$	0.470	$\frac{29}{32}$ max.
	RW-42	60	33	18	25	4	$1\frac{5}{32}$	0.690	$1\frac{5}{16}$ max.
	RW-43	78	45	22	50	6	$1\frac{5}{32}$	0.690	$1\frac{5}{16}$ max.
	RW-44	100	57	30	80	8	$1\frac{5}{32}$	0.690	$1\frac{5}{16}$ max.
	RW-45	155	86	43	100	12	$1\frac{5}{32}$	0.690	$1\frac{5}{16}$ max.
Axial-tab terminals Fig. 3·2*e*	RW-50	5	5	2	4	$\frac{9}{16}$	$1\frac{3}{8}$	$\frac{5}{32}$	$\frac{7}{16}$ to $\frac{5}{8}$
	RW-51	10	9	4	6.3	$\frac{9}{16}$	2	$\frac{5}{32}$	$\frac{7}{16}$ to $\frac{5}{8}$
	RW-52	25	19	9	10	$\frac{5}{8}$	$2\frac{7}{8}$	$\frac{3}{16}$	$\frac{19}{32}$ to $\frac{25}{32}$
	RW-53	50	25	18	25	$\frac{5}{8}$	4	$\frac{3}{16}$	$\frac{13}{16}$ to $\frac{15}{16}$
	RW-54	120	60	42	50	$\frac{5}{8}$	$8\frac{15}{16}$	$\frac{3}{16}$	$\frac{15}{16}$ to $1\frac{3}{16}$
Axial wire leads Fig. 3·2*f*	RW-55	5	5	2	4	$1\frac{3}{8}$			
	RW-56	10	9	4	6.3	2			

* With 2.5-mil wire.

low resistances the letter *R* may be used for the decimal point; thus 2R5 would mean 2.5 ohms, and R25 would mean 0.25 ohms.

The useful life of wire-wound resistors depends upon the maximum short-time and the average continuous operating temperatures, the presence of moisture or other agents that promote corrosion, and mechanical conditions such as shock and vibration. It is evident from the table above that the Grade 1, Class I resistor, Characteristic F, will withstand

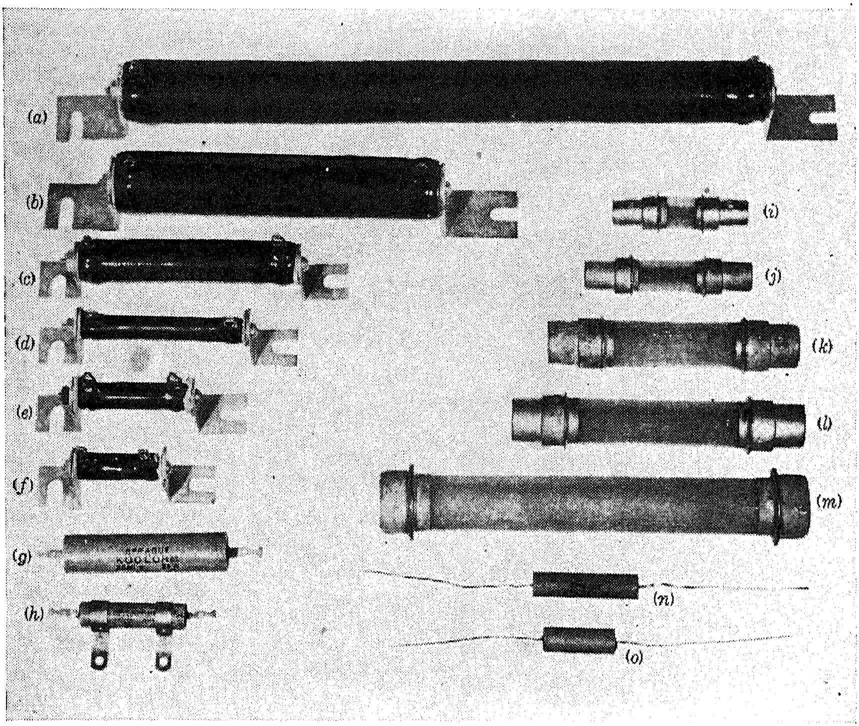

FIG. 3·3.—Typical power-type resistors. (*a*) RW-39; (*b*) RW-37; (*c*) RW-35; (*d*) RW-33; (*e*) RW- 32; (*f*) RW-31; (*g*) RW-53; (*h*) RW-51; (*i*) RW-16; (*j*) RW-15; (*k*) RW-14; (*l*) RW-13; (*m*) RW-12; (*n*) RW-56; (*o*) RW-55.

the most severe service usage without sacrificing wattage rating for a given physical size. A resistor of this type can be made, at present, only by hermetically sealing the resistor element into a rugged Pyrex tube. Such a unit will withstand nine salt-water immersion cycles. Certain organic coatings applied to conventional open-type resistors will also meet the Grade 1 test but these invariably require derating to limit the maximum temperature to about 150°C, thus fitting them into Class III. Further information on derating factors is given in Sec. 3·4. Resistors of characteristics E, F, and H will withstand at least nine salt-water immersion cycles, at the end of which they are not expected to have

changed by more than 10 per cent from their initial value. Characteristic D resistors are expected to withstand two test cycles. The grade 3 resistors, Characteristics C, G, and J, are required to withstand a 500-hr cyclic temperature test at high humidity. At the end of the tests the resistance is not to have changed by more than 5 per cent. Resistors of all classes and grades are expected to withstand continuous vibration for a period of 5 hr, cycling through a frequency range of 10 to 55 cps with a half-amplitude of 0.03 in. A mechanical-strength test is specified calling for a transverse load of 50 lb (25 lb for stack-mounting) applied at the

TABLE 3·3.—POWER-TYPE WIRE-WOUND RESISTOR CHARACTERISTICS

Letter	Class	Grade
C	II	3
D	I	2
E	II	1
F	I	1
G	I	3
H	III	1
J	III	3

TABLE 3·3*a*

Class	Maximum continuous operating temperature, °C
I	275
II	125
III	200

TABLE 3·3*b*

Grade	Resistance following thermal shock
1	Most resistant to salt-water immersion
2	Less resistant to salt-water immersion
3	Resistant to humidity exposure

center of the resistor through a fulcrum having a radius of 0.25 in. or less. For this test the resistor is supported 0.125 in. from either end. A thermal shock test is required as a check on the coating material and on the quality of the joint between the end of the resistance wire and the terminal. This shock test consists of applying rated power to the resistor for a time long enough to allow it to reach thermal stability, then plunging it into water at 0°C (for Characteristic D, E, F, and H resistors) or immediately subjecting it to an air temperature of −55°C (for Characteristic C, G, and J resistors). After the thermal shock test, the resistor is not to have changed by more than 2 per cent, and the coating and terminals should show no observable mechanical damage. In the actual

TABLE 3·4.—PROPERTIES OF RESISTANCE-WIRE ALLOYS

Name	Composition, %					Resistivity		Temperature coefficient	Temperature range, °C*	Max. working temperature, °C	Manufacturer
	Ni	Cr	Cu	Fe	Mn	Microhm-cm	Ohms per circular mil foot				
Nichrome V	78	20	..	1	1	108	650	130×10^{-6}	20–100	1100	Driver-Harris
Tophet A	80	20	..	..	..	108	650	140	20–100	1150	W. B. Driver
Chromel A	80	20	..	..	..	108	650	110	20	1100	Hoskins
Cupron	45	..	55	..	..	49	294	±20	20–100	500	W. B. Driver
Advance	45	..	55	..	..	49	294	±20	20–100	535	Driver-Harris
Manganin	4	..	84	..	12	48.2	290	±15	15–35	100	W. B. Driver
											Driver-Harris
180 Alloy	22	..	78	..	..	29.9	180	160	20–100	400	W. B. Driver
90 Alloy	12	..	88	..	..	14.9	90	380	20–100	400	W. B. Driver

Similar to Nichrome V: Superior.
" " Chromel A: Chronin, Nichrome III.
" " Advance: Constaloy, Excelsior, Constantan, Ideal.
" " Manganin: Tarnac.

* Temperature range over which given temperature coefficient applies. For most alloys, useful working temperature range is much greater than given above.

See also Fig. 3·4.

testing procedure the thermal shock test precedes the salt-water-immersion or the moisture-resistance test, whichever applies.

3·2. Construction.—Standard power-type wire-wound resistors are wound of alloy resistance wire on ceramic forms, usually porcelain tubes, and the wound units are coated with a vitreous enamel or an organic cement. The resistance materials used are almost always either nickel-chromium or copper-nickel alloys. Some of the characteristics of the most-used alloys are given in Table 3·4. A collection of data on resistance wires will be found in Table 8·1 of Chapter 8.

The alloys used for wire-wound resistors may be divided into two groups: the nickel-chromium alloys, of which the Nichromes are typical, and the copper-nickel alloys of the Advance type. There are other resistance alloys that do not belong to either of these groups, but they are not commonly used for fixed resistors of the types under discussion. In general the nickel-chromium alloys have a high resistivity (about 600 ohms per circular mil ft) and a high temperature coefficient (about $150 \times 10^{-6}/°C$) which is substantially constant up to about 400°C. The copper-nickel alloys, particularly those with nickel contents of 40 per cent or more, have lower resistivities (300 ohms per circular mil foot or less) and much lower temperature coefficients which may be either positive or negative and which vary considerably over the temperature range 0° to 400°C.

The resistivities and especially the temperature coefficients of resistivity of all types of resistance alloy are greatly affected by slight variations in alloy composition and by variations in the metallurgical treatment following the last annealing operation. Wire that is cooled slowly has a higher resistivity and a lower temperature coefficient than the same wire that is quenched from the last anneal. The problem of metallurgical stabilization is important if the temperature coefficient of resistivity is to be held within close limits. For example, special processing is necessary to hold Nichrome V wire to a maximum of $100 \times 10^{-6}/°C$ and a minimum of $65 \times 10^{-6}/°C$ over the range 20° to 100°C. Uniform resistors can be made only if the wire is uniform as to metallurgical treatment, cross-sectional area, and circularity, and is free from scales, pits, slivers, seams, die marks, and corrosion.

Figure 3·4 shows the variation of resistance with temperature for five of the more common resistance alloys. In Fig. 3·4*a* the "minimum" curve is for wire that has been slowly cooled from 1000°C; the "maximum" curve is for wire that has been quenched; and the "average" is for the bright-annealed wire that is usually used for resistors.

The most widely used alloys for power-type resistors are those of the Nichrome V group. In order to obtain the highest possible degree of long-time resistance stability and uniformity of temperature coefficient

the wire must conform to a rigid set of specifications, such as the Bell Telephone Laboratories Specification KS-9140. This specification requires

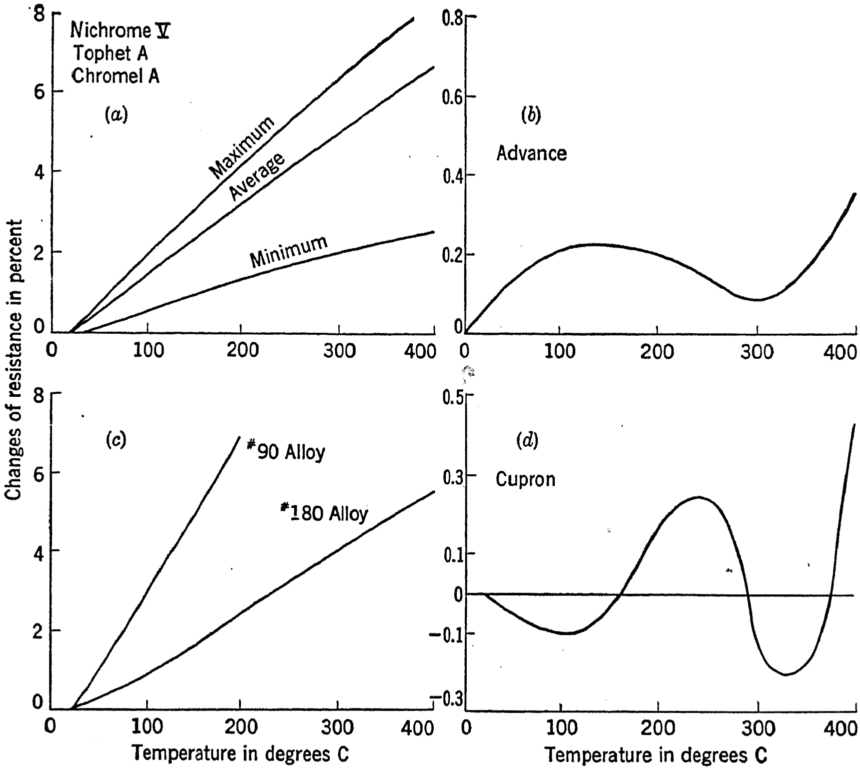

FIG. 3·4.—Variations of resistance with temperature.

the following electrical and mechanical characteristics:

1. The temperature coefficient of resistivity between 20° and 100°C is to be between 100×10^{-6} maximum and 65×10^{-6} minimum per degree centigrade.
2. The resistance tolerance is to be ± 5 per cent for wire sizes AWG 30 to 36, ± 8 per cent for sizes 37 to 44, and ± 10 per cent for size 45. (See Table 8·1, Chap. 8 for nominal values.)
3. The minimum tensile strength is to be 100,000 lb/in.^{2}
4. The elongation in an 8-in. test piece is to be 20 per cent, minimum, for wire 0.010- to 0.040-in. diameter; 10 per cent for wire 0.0035- to 0.00175-in. diameter.

Windings.—Most power-type resistors are wound with bare wire on cylindrical porcelain forms with the turns widely spaced to reduce the probability of short circuits. JAN-R-26 specifies a maximum pitch of

not over 2.25 times the wire diameter for wires up to 10-mil (0.0100 in.) diameter and not over 2.75 times the diameter for larger wires. The minimum wire diameter according to the same specification is 2.5 mil nominal (2.4 mil absolute minimum), but commercial resistors are wound of wire down to 1.5 mil and are satisfactory for most purposes. The use of ceramic insulation on the wire permits several other types of winding. One is analogous to the "coiled coil" used in incandescent lamp filaments; the insulated wire is formed into a close-wound helix of a diameter of several times that of the wire, and this helix is then close-wound on the resistor form. Another type is the progressive universal winding, which is also used on some low-frequency r-f coils and is there called "bank winding." In this winding the wire is fed through a guide that oscillates parallel to the axis of the resistor form with an amplitude of perhaps $\frac{1}{16}$ in. as the form rotates and with a period of somewhat more or less than the rotational period of the form. The guide advances along the form a fraction of a wire diameter per turn. The result of this rather complicated motion is that the wire builds up to a thickness of perhaps 12 layers, the turns crossing and recrossing each other as in a regular universal winding. The winding is somewhat open and has a low distributed capacitance and a fairly low voltage between adjacent turns. It permits resistances of up to $2\frac{1}{2}$ times the maximum obtainable with a single-layer winding of the same wire on the same form, with only a negligible increase in over-all diameter.

All these windings possess residual inductance and capacitance which seriously affect their alternating-current properties at high frequencies (as will be discussed in Sec. 3·5), and many constructions have been devised to reduce these quantities. By using a winding in which the adjacent turns carry current in opposite directions, the inductance is minimized; by spacing the turns as far apart as possible and keeping the potential difference between turns to the lowest possible value, the capacitive effects are reduced. Resistors made with such special patterns are termed "noninductive," but this term is only relative since the time constant at 10 Mc/sec for a high-grade 1000-ohm resistor will be about 0.1 μsec.

The type of noninductive winding most commonly used is the Ayrton-Perry, which is made by winding a spaced helix between the terminals, after which a second helix is wound in the opposite direction between the turns of the first. The two windings are connected in parallel so that the resultant magnetic field is small and the capacitive effects are at a minimum because of the low voltage between adjacent turns. Such a construction, because of the parallel connection, reduces the resistance that can be obtained in any given physical size by a factor of at least 2 for single-layer windings and by a much larger factor for multilayer pro-

gressive windings. Some comparative figures for the maximum resistance values obtainable with standard and Ayrton-Perry windings are given in Table 3·5. The type of resistor to which the table refers is an

TABLE 3·5.—MAXIMUM RESISTANCE OF FERRULE-TERMINAL RESISTORS

Resistor style	Rating at 20°C, w	Type of winding	Maximum resistance, ohms	
			1.5-mil wire	2.5-mil wire
RW-16	15	Standard Single-layer	12,700	3150
		Progressive	30,000	......
		Ayrton-Perry	6000	1500
RW-15	20	Standard	17,500	4000
		Progressive	50,000	......
		Ayrton-Perry	8000	2000
RW-14	40	Standard	53,000	12,500
		Progressive	75,000	......
		Ayrton-Perry	25,000	6000
RW-13	50	Standard	63,000	16,000
		Progressive	100,000	......
		Ayrton-Perry	30,000	8000
RW-12	90	Standard	140,000	31,500
		Progressive	200,000	......
		Ayrton-Perry	70,000	15,000

insulated-wire glass-enclosed ferrule-terminal sealed unit used widely where severe humidity and atmospheric conditions are to be met. The 90-, 40-, and 15-watt resistors are shown in Fig. 3·5.

Coatings.—Power-type wire-wound resistors must be protected after winding either by insertion in a glass or porcelain outer shell or by a suitable ceramic or organic-cement coating. The glass-shell construction is exemplified by the JAN styles RW-10 through RW-16; these units employ the solder-seal technique to attach the ferrule terminals to the shell and to obtain complete hermetic sealing of the winding against the entry of moisture or other corrosive agents. Most Sprague "Koolohm" resistors employ a somewhat simpler construction in which the ceramic-insulated wire resistor with terminals attached is slipped into a porcelain shell and sealed in place with a ceramic cement. The great majority of power resistors, however, are wound with bare wire and therefore demand some sort of coating or impregnation, both for protection of the wire against moisture and for holding the turns in place on the winding form.

These coatings may be either inorganic or organic. The inorganic coatings are vitreous or semivitreous enamels similar to those used on enameled kitchenware and bathroom fixtures, but with special character-

istics required by the resistors. A good resistor coating should have approximately the same coefficient of thermal expansion as the resistance alloy (this also applies to the porcelain winding form); it should be reasonably resistant to mechanical abuse; it should withstand severe thermal shocks without chipping or crazing; it should be impervious to moisture; and it should be easily applied and cured at a temperature low enough to prevent damage to the resistor. No coating has been developed that is

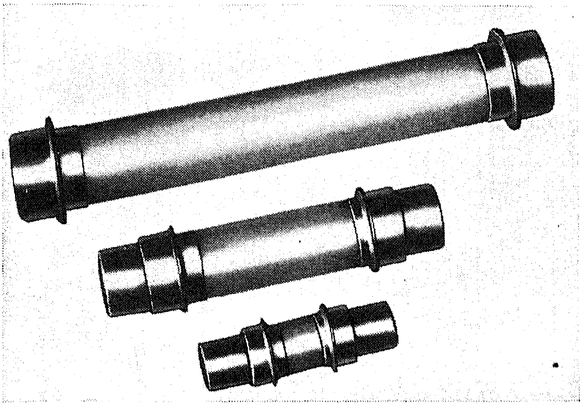

FIG. 3·5.—Ferrule-terminal resistors. From top down, respectively: RW-12; RW-14; RW-16.

completely satisfactory in all these respects and is at the same time able to withstand continuous operation at high temperatures. Glassy inorganic enamels are satisfactory in many respects but are somewhat pervious to moisture and are often subject to damage by thermal shock. Other inorganic enamels have been developed which are highly resistant to thermal shock but which are somewhat porous and offer insufficient moisture protection to fine-wire windings used in corrosive environments. Inorganic enamels, however, permit continuous operation at hot-spot temperatures as high as 275°C.

Organic coatings have been developed that are satisfactory in all of the above respects except that they limit the maximum operating temperature to their curing temperature, which is ordinarily from 130° to 160°C. These coatings usually employ a phenolic-resin varnish with a comparatively large proportion of inorganic filler, such as silica flour, mica flour, or iron oxide. They are highly resistant to moisture and to thermal shock, and can be made to pass the salt-water-immersion test specified in JAN-R-26. The problem of lack of resistance to high temperatures may be solved in the near future by the use of the heat-resistant silicone varnishes, some of which are good up to 500°C. At present, however, the only resistors to receive a Class F rating (see Sec. 3·1) are those sealed in glass tubes.

Too much emphasis should not be put on operation at extreme temperatures. It would be possible to build a rugged resistor for continuous operation at 1000°C, but it would hardly be practical to use it at that temperature in the average chassis. Resistor operating-temperature limits are probably set more often by the neighboring components in the chassis than by the resistor itself.

Leads and Mountings.—Connection between the ends of the winding and the terminals is made by soldering or welding the wire to terminal bands or lugs or by embedding them in alloy castings encircling

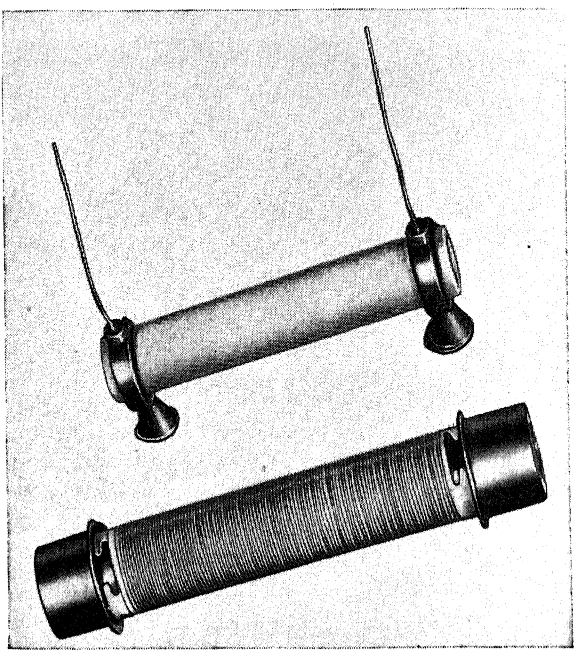

FIG. 3·6.—Resistor terminal constructions. The upper unit is an unfinished wire-wound resistor with die-cast terminals. The winding had been removed before the photograph was taken, leaving a short end of wire visible only in the original print. The conical gates would be clipped off in production, leaving only the radial wire leads protruding through the insulating coating of the finished resistor. The lower unit is an RW-12 minus its protecting glass sleeve.

the ceramic winding form. Both methods are illustrated in Fig. 3·6. Besides the JAN-standardized terminals of Fig. 3·2 many other types are available on commercial resistors, either standard or on special order. These include stranded wire leads, either bare or insulated with beads or sleeving; Edison medium screw bases to permit the use of the resistor in a standard electric light socket; single-hole mountings with mounting nut similar to that often used with filter condensers, the winding being terminated on soldering lugs at the threaded end of the unit; ferrules of various sizes and shapes, including conical ferrules to permit mounting in

grid-leak clips; live brackets, with the winding terminated on the mounting brackets; and various others. The mounting devices are even more varied than the terminals. In some cases, as with the live-bracket and ferrule-terminal types, the units are mounted by the terminals. In others, such as the stack-mounting resistors, the mounting is mechanically integral with the unit, but separate insulated terminals are provided. In still others, means for separate mounting are required, and the manufacturers offer a wide choice of mounting hardware.

The JAN specifications require that terminals pass certain mechanical tests which are fairly severe in cases where the units are supposed to be mounted by their terminals. In general, mounting by the terminals is forbidden except for the smallest sizes of resistor. All wire-wound resistors, except the tiny RU styles and the types with integral mounting means, should always be mounted by suitable brackets, clips, or through-bolts. Where bare porcelain cores are exposed they should never be screwed or clamped to metal panels or brackets without a cushioning washer of asbestos, mica, or fiber. Because of their fragile flanges this precaution is particularly important for bobbin-wound precision resistors.

3·3. Resistance Values; Tolerances and Variations.—The maximum resistance obtainable in a given physical resistor size depends upon the minimum permissible wire size, the form of winding (single-layer, multilayer, or noninductive), and the maximum permissible operating temperature of the completed resistor. The JAN values for maximum resistance given in Table 3·2 are based on the use of single-layer windings of 2.5-mil wire. Not all applications require that the wire be so large or that the winding be restricted to a single layer. For ordinary industrial or laboratory uses where corrosive conditions are much less severe than in military applications 1.4- or 1.5-mil wire can be specified with reasonable assurance of long resistor life. If the hermetically sealed glass-enclosed form of resistor is used, the greater protection so afforded permits the use of the smaller wire even under unfavorable environmental conditions. Table 3·5 presented a comparison of maximum resistance values obtainable in such a resistor for 2.5-mil and 1.5-mil wire, single-layer, multilayer, and noninductively wound. It is seen that in going from 2.5 to 1.5 mil, single layer, the maximum obtainable resistance is increased by a factor of approximately 4, and in going from a single-layer 1.5-mil wire to a progressive winding of the same size wire, the factor is $1\frac{1}{2}$ to 3. It must be pointed out, however, that the use of progressive or multilayer windings will reduce the wattage rating for a given physical resistor size and full information on the reduction factor should be obtained from the manufacturer. Despite this reduction, such windings afford considerable economy in space, particularly in applications where the actual dissipation is small compared to the dissipation capability

that is inherent in the resistor because of the physical size required for the necessary resistance.

Further information on the maximum obtainable resistances for three other types of resistor is given in Table 3·6. Part *a* of Table 3·6 refers to the commonly used cylindrical resistor with radial soldering lugs, Part *b* to axial-lug ceramic-sheathed resistors with a coiled-coil winding of ceramic-insulated wire (Sprague "Koolohm" construction), and Part *c* to flat stack-mounting or "ribbon" resistors.

TABLE 3·6.—MAXIMUM RESISTANCE VS. WIRE SIZE AND TYPE OF WINDING

JAN Type	Wattage	Resistance, ohms		
		2.5-mil wire	1.5-mil wire	Noninductive
a. Radial-lug type resistors				
RW-30	7	1,000	2,500	3,000
RW-32	16	4,000	16,000	3,000
RW-33	24	16,000	37,500	3,000
RW-34	30	16,000	50,000	3,000
RW-35	38	20,000	72,500	5,000
RW-36	60	40,000	120,000	5,000
RW-37	78	50,000	180,000	5,000
RW-38	100	80,000	340,000	5,000
b. Axial-lug type resistors				
RW-50	5	4,000	40,000	5,000
RW-51	10	6,300	70,000	10,000
RW-52	25	10,000	100,000	25,000
RW-53	50	25,000	100,000	50,000
RW-54	120	50,000	250,000	100,000
c. Stack-mounting resistors				
RW-20	22	2,000	6,300	
RW-21	31	5,000	15,800	
RW-22	48	10,000	35,000	
RW-23	60	16,000	50,000	
RW-24	70	20,000	66,000	

Standard Resistance Values.—The actual resistance values specified as standard by JAN-R-26 follow a preferred number system rather like that used for composition resistors, but with fewer values per decade. The succession of values runs 10–12–16–20–25–31–40–50–63–80– and repeats in succeeding decades. Since the standard tolerance is ± 5 per cent for most values, it is obvious that there are numerous resistance ranges that cannot be covered with standard resistors, but for any appli-

cation in which power-type resistors would be likely to be used the resistance tolerance should be large enough to render this objection immaterial. The standard minimum resistance is 0.10 ohms for all JAN types except RW-10, for which it is 2.0 ohms. The standard tolerance for RW types is ± 5 per cent except for values less than 1.0 ohm, when it is ± 10 per cent. For tapped resistors which are standard in performance and in construction except for the taps the tolerance is ± 10 per cent for the individual sections and ± 5 per cent for the over-all resistance. The low-power RU resistors are made in two series, with ± 5 and ± 10 per cent tolerances.

A perusal of the catalogues of a number of resistor manufacturers indicates that few if any of them adhere to the conventions of the previous paragraph for either stock resistance values or standard tolerances. A typical list shows very few stock sizes per decade in either very high or very low values, whereas in the commonly used ranges there may be 15 or more stock sizes per decade. This condition is due to two facts. First, a manufacturer will naturally list only those sizes for which he has found there is an appreciable demand. If, for example, there are two popular audio-output tubes that require 10-watt cathode resistors and the tube handbooks give 550 ohms as the correct value for one and 600 ohms for the other, the manufacturer will probably list both of these values, even though neither is standard and though either of the standard values of 500 and 630 ohms would probably be just as suitable in the average receiver. On the other hand, since an order for 0.63-ohm resistors of a particular type would probably be received only once in many months the manufacturer would probably prefer to consider this a special value, to be made up when the order is received. Second, although the susceptibility of the exposed wires of adjustable resistors to mechanical damage and corrosion has led to their being banned by the Armed Services for use in combat equipment, they are quite satisfactory for many commercial applications and offer a solution to the problem of obtaining intermediate resistance values that is itself a sufficient excuse for eliminating rarely wanted items from a stock list.

Somewhat more uniformity is found among the manufacturers in the matter of standard tolerances. Most of them specify ± 5 per cent as standard, increasing this to ± 10 per cent below 50 ohms. Others list only ± 10 per cent wire-wound resistors, and many manufacturers list other tolerances as obtainable on special order at an increased price.

Temperature Coefficient.—Practically the only variable that has an appreciable effect in changing the resistance of a wire-wound resistor is temperature, and the temperature coefficient of the resistor is approximately that of the resistance wire itself. Considerable latitude is given in the JAN-R-26 specification which permits a coefficient, referred to

26°C, of $400 \times 10^{-6}/°C$ for resistors up to 50 ohms and $260 \times 10^{-6}/°C$ for resistors over 50 ohms. For the usual accuracy requirements of power-type resistors the change of resistance with temperature can be estimated satisfactorily from the curves of Fig. 3·4. A measurement of the rise of resistance at a single elevated temperature will usually show whether the wire used is of the high- or the low-temperature-coefficient type, if this information is not otherwise available. To determine the actual variation of resistance in service, however, it is necessary to take into account the fact that the average temperature of the winding will normally be less than the maximum hot-spot temperature and will depend markedly on the cooling conditions. Ordinarily the percentage of rise in resistance is about two-thirds of that given by the product of hot-spot rise and temperature coefficient.

3·4. Ratings.—The dissipation ratings of power-type resistors are based on the maximum permissible temperature rise when operating in still air and suspended in free space with an ambient temperature of 25°C. Still air is defined as air with no circulation other than that created by the heat of the resistor in operation. Free space is defined as that in which no object is closer than 12 in. to the resistor coating except the mounting clip, which must be at least 2 in. below the unit. The resistor is to be mounted horizontally. The temperature is measured at the hottest spot on the surface, using a thermocouple hung over the resistor with its leads weighted by a load of 2 oz to provide for pressure of the thermocouple junction against the uppermost portion of the resistor surface. The couple is made of No. 30 AWG wire or smaller, lap-welded. Resistors are classified on the basis of wattage dissipation under the conditions described above for which the maximum hot-spot temperature will not exceed a specified value. This value depends on the type of construction and the material used for protective coating. High-temperature refractory coatings allow a maximum hot spot of 275°C; moisture-resistant organic cements are generally limited to a maximum hot spot of about 160°C with a consequent reduction in rating to about 40 per cent of the first type. Figure 3·7 shows the temperature rise of a Class I resistor of the radial-lug type, plotted against per cent of rated dissipation. It is evident from such a curve that the useful practical wattage rating of a resistor must be something less than the free-air

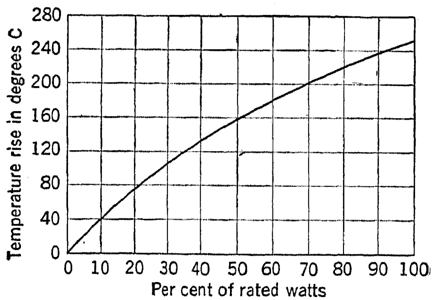

FIG 3·7.—Temperature rise vs. dissipation for Class I resistor at 25°C ambient temperature.

rating since the latter condition is never achieved in actual use. Some of the necessary considerations are summarized in the "Use Notes" which are a part of specification JAN-R-26.

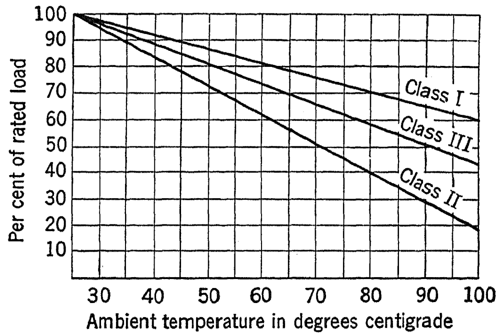

FIG. 3·8.—Derating curves for high ambient temperatures. Class I: 275°C maximum hot spot. Class II: 125°C maximum hot spot. Class III: 200°C maximum hot spot.

1. For ambient temperatures higher than 25°C, a derating factor should be used to normalize to the value for which the resistor is rated at 25°C (see Fig. 3·8).
2. When resistors are mounted in enclosures that limit ventilation, the wattage dissipation of any resistor should be reduced so that the maximum hot-spot temperature permissible for the resistor is never exceeded under the most severe combination of temperature conditions.
3. When resistors are mounted in rows or banks they should be so spaced that, taking into consideration the restricted ventilation and heat dissipation by the near-by resistors, none of the resistors in the bank or row exceeds its maximum permissible hot-spot temperature. It is difficult to give a definite factor but reduction in ratings of 50 per cent may frequently be necessary.
4. The styles of resistors should be so chosen that, as mounted in equipment, they will at no time operate at temperatures in excess of their rating. More specifically, this applies to equipment operating as follows:
   a. In the maximum specified ambient temperature.
   b. Under conditions producing maximum temperature rise in each resistor.
   c. For a sufficient length of time to produce maximum temperature rise.
   d. With all enclosures in place.
   e. With any special conditions imposed which are possible during the life of the equipment, as at high altitude for airborne apparatus.

Voltage Rating.—Because of the comparatively large physical size of wire-wound resistors and the fact that inherently the voltage gradient can be uniformly distributed, the limiting operating voltage is established in most cases by the wattage rating and resistance value of the unit. One important exception is the limitation introduced by some types of coating when operated at the high temperatures corresponding to full wattage ratings, since these coatings under such conditions are poor insulators. In general it is necessary to limit the voltage, across the terminals of a vitreous-enamel-coated resistor operating at its maximum temperature, to about 500 volts. This limitation may be introduced in other types of resistor for the largest units; for example, a 250,000-ohm, 150-watt resistor. If the coating of such a resistor is not considered, the power rating would permit 6100 volts but because of the coating the actual rating of the manufacturer might be 5000 volts.

Another element to be examined is the voltage limitation of the resistor insulation between terminals and mounting hardware. The JAN specification requires that all resistors, except the ferrule-terminal types, withstand 1000 volts rms at 60 cps between the resistor terminals connected together and the mounting hardware or metal plates in contact with the ends or surface of the resistor. The insulation resistance between terminals and mounting hardware after this test is required to be not less than 50 megohms. If there is to be a high potential between the resistor and a grounded surface on which it is to be mounted, it will be necessary to provide additional insulation in the form of ceramic bushings or other heat-resisting insulators.

3·5. Alternating-current Characteristics.—The behavior of wire-wound resistors at high frequencies is affected to a considerable extent by the inductance and capacitance that are inherent in their construction (see Sec. 3·2). Skin effect is not particularly troublesome because of the small-size wire generally used. Some indication of the magnitude of skin effect is given in Table 3·7, which shows the largest permissible wire size for a skin-effect ratio of 1.01, calculated for a cylindrical straight wire remote from other conductors.

TABLE 3·7.—SKIN EFFECT IN RESISTANCE WIRES

Frequency, kc/sec	Wire size, mils				
	Nichrome	Manganin	Constantan	Advance	Copper
100	104.5	70.2	74.5	71.6	14.0
1,000	33.0	22.2	23.5	22.4	4.4
3,000	19.2	12.8	13.6	11.8	2.6
10,000	10.4	7.0	7.5	7.2	1.4

Inductive and capacitive effects are not so easily disposed of. Because of the difficulty of separating these parameters and in determining reactances of high-resistance components, little useful information is available either in the form of an applicable lumped-constant analysis or in that of actual experimental data. The common procedure used by resistor manufacturers to find the inductance of a wire-wound resistor is either to calculate it from standard inductance formulas or to make up a similar unit with copper wire and to measure its inductance. More recently, this practice is being replaced by measurements made on actual resistors and suitable techniques are being applied so that some information can be obtained for resistors of moderate value.

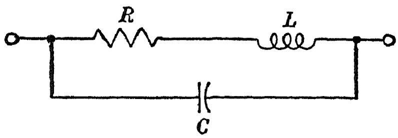

FIG. 3·9.—Equivalent circuit of a wire-wound resistor.

The most practical circuit representing a wire-wound resistor at high frequencies is shown in Fig. 3·9.

Definite values can be assigned to the components of this circuit at any one frequency, and these, with certain limitations, will be reasonably valid over a wide range of frequencies. The errors in such a circuit, if R is taken as the d-c resistance, are due to the following factors:

1. The capacitance and inductance are distributed, not lumped.
2. There are dielectric losses present in the insulation and coating.
3. There may be a skin effect with large wire and at very high frequencies.

There is therefore a limiting frequency at which the simple circuit no longer is applicable, depending on the type of resistor and the permissible error in calculations.

For measurements of conductance and effective parallel capacitance of typical wire-wound resistors at frequencies between 1 and 35 Mc/sec, a twin-T impedance measuring circuit has been used.[1] This method of measurement is more suitable in the megacycle range of frequencies where the usual series method giving effective values of series resistance and reactance affords no simple or direct capacitance measurement.

The parallel method applied to the equivalent circuit gives the admittance.

$$Y_e = \frac{R}{R^2 + (\omega L)^2} + j\omega \left[C - \frac{L}{R^2 + (\omega L)^2} \right].$$

Since the inductance and capacitance are already fairly well separated,

[1] D. T. Drake, "High Frequency Characteristics of Resistors," RL Report No. 520, Mar. 9, 1944.

no difficulty is involved in their calculation when the conductance and susceptance are known. If the resistance is assumed equal to the d-c value the inductance can be determined directly in terms of the parallel conductance and d-c resistance from the equation

$$L = \frac{\sqrt{R/g - R^2}}{\omega}$$

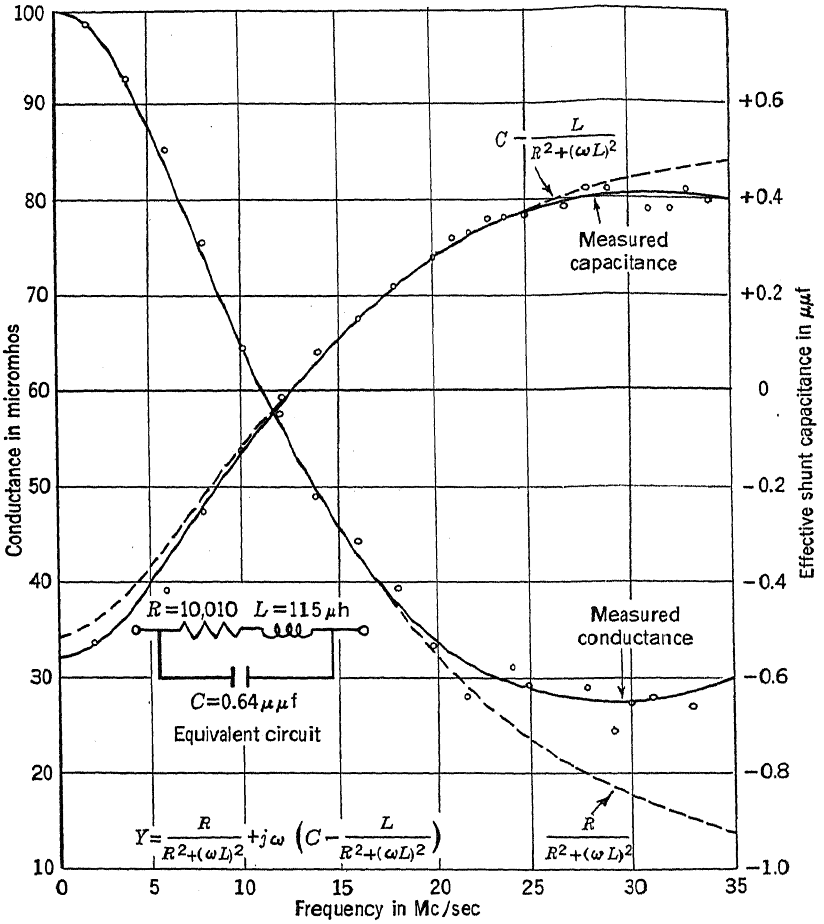

FIG. 3·10.—High-frequency characteristics of IRC type AB resistor.

An accurate determination of the capacitance is more of a problem because of the difficulty in obtaining accurate measurements of values which are generally 1 $\mu\mu$f or less. One can ordinarily be satisfied with an approximate solution, however, because the inherent capacitance of a resistor is usually small in comparison to circuit-wiring and vacuum-tube capacitances.

Figure 3·10 shows the experimental and the calculated values of capacitance and conductance for a typical 10-watt 10,000-ohm IRC type AB cylindrical single-layer power-type resistor. It is seen that the equivalent circuit in which $L = 115\ \mu$h and $C = 0.64\ \mu\mu$f is valid up to about 17 Mc/sec.

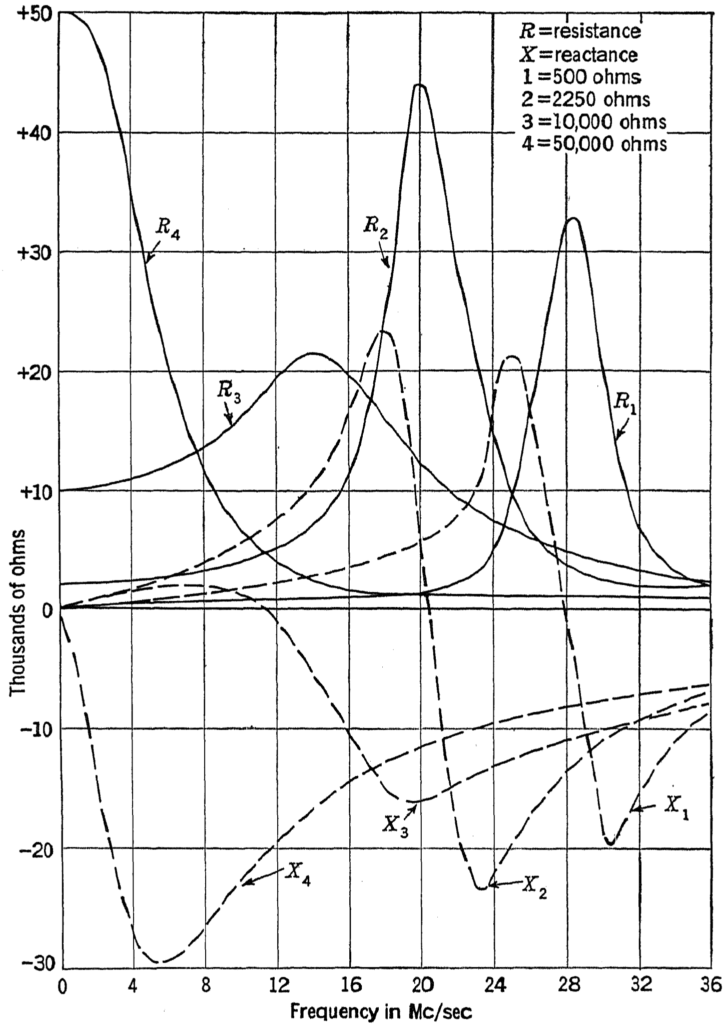

FIG. 3·11.—High-frequency characteristics of wire-wound resistors.

Figure 3·11 is a set of curves showing the high-frequency characteristics of cylindrical single-layer power-type resistors ranging in value from 500 to 50,000 ohms over the frequency range from 0 to 36 Mc/sec. It is evident that the reactance may be either inductive or capacitive,

depending on the frequency, and that the actual impedance may differ from the d-c resistance by a factor of 10 or more. No general rules of variation can be given because the performance of a particular resistor will depend on the number of turns, spacing, and physical dimensions and these, in turn, on the wire size, wattage rating, and resistance value. Table 2·11 gives values of inductance for a range of resistance values of 10-watt single-layer resistors. These are intended to give order of magnitude only, since the method by which they were measured has not yet been thoroughly examined and confirmed as completely reliable.

TABLE 3·8.—INDUCTANCE OF 10-WATT SINGLE-LAYER RESISTORS
(Length = $1\frac{3}{4}$ in.; Diameter = $\frac{5}{16}$ in.)

Resistance, ohms	Inductance, μh	Resistance, ohms	Inductance, μh
1000	56	6,000	201
1250	47.5	7,000	186
1500	73	7,500	205
2250	72	10,000	115
2500	88	12,000	282
3000	84	12,500	75
3500	118	15,000	315
4000	176	50,000	735
4500	114		

Special windings are obtainable in power-type resistors to reduce the inductance to much lower values than are obtained with simple solenoidal or progressive windings. The Ayrton-Perry winding is generally used for the so-called noninductive resistors. Table 3·9 gives comparative inductance values for standard and noninductive windings on cylindrical coated power-type resistors.

TABLE 3·9.—INDUCTANCES OF STANDARD AND AYRTON-PERRY WINDINGS
(Data from IRC Catalog 38)

IRC type	Wattage rating	Resistance, ohms	Physical size, length and diameter, in.	Inductance, μh	
				Standard	Ayrton-Perry
AB	10	1000	$1\frac{3}{4} \times \frac{5}{16}$	66	0.6
DG	20	100	$2 \times \frac{9}{16}$	14	0.25
EP	50	80	$4\frac{1}{2} \times \frac{3}{4}$	76	0.3
HA	100	4000	$6\frac{1}{2} \times 1\frac{1}{8}$	3360	0.3

As has been pointed out, the inductance of a resistor cannot, in itself, establish its high-frequency properties. Capacitive effects become increasingly important with increasing frequency. For example, at 3

Mc/sec the reactance of a 15-watt RW16F resistor becomes capacitive for a value of 300 ohms. For a 120-watt resistor of the same type, all values over 250 ohms are capacitive. It is evident that there is not much to be gained by insisting on noninductive windings for resistance values above a few hundred ohms, at this frequency. This point is demonstrated in Table 3·10, which gives the phase angles for three types of winding of ferrule-mounting resistors, style RW16F and RW11F with 15- and 120-watt ratings, at a frequency of 3 Mc/sec.

TABLE 3·10.—REACTANCE OF SPRAGUE WIRE-WOUND RESISTORS AT 3 MC/SEC

Style of winding	Phase angle	
	RW16F 15 watts 100 ohms (lag)	RW11F 120 watts 1000 ohms (lead)
Standard (type F)	60°57′	57°20′
Noninductive (type NIF)	6°22′	22°
"Super" noninductive (special winding)	2°15′	14°20′

ACCURATE WIRE-WOUND RESISTORS

3·6. Standard Types.—There are many applications in electronic circuits where accuracy and stability requirements are greater than can be met with power-type resistors but where the power dissipation is so low that surface hot-spot temperatures can be kept to a maximum of 105°C. For such applications a number of types of resistor have been developed that may be called "accurate wire-wound resistors." The term "precision resistors" is also commonly used. These units are small in size, wound of fine insulated resistance wire, usually in deep narrow slots in ceramic or plastic bobbins, and are widely used in d-c amplifiers, computing networks, linear sweep generators, multivibrators, and similar applications where resistance tolerances of ± 1 per cent or better are required.

Much of the material on power-type resistors in Secs. 3·1 through 3·5 is also applicable to the accurate resistors. This section and the two following will present additional information specifically relevant to the accurate types.

Two Joint Army-Navy Specifications cover accurate wire-wound resistors: JAN-R-93, "Resistors, Accurate, Fixed, Wire-Wound," and JAN-R-29, "Resistors, External Meter (High Voltage, Ferrule Terminal Type)." Outline drawings of the five classes of resistor of JAN-R-93 and the one of JAN-R-29 are given in Fig. 3·12; the dimensions and characteristics of the various styles are given in Tables 3·11 and 3·12.

Table 3·11.—Accurate Wire-wound Resistors

	JAN-R-93 style	Nominal power rating, watts	Resistance		Dimensions, in.			
			min., ohms	max., megohms	*A* min.	*A* max.	*B* max.	*C*
Radial-lug terminals (Fig. 3·12*a*)	RB-10	$\frac{1}{4}$	0.1	0.185	...	$\frac{15}{32}$	$\frac{3}{4}$	....
	RB-11	$\frac{1}{3}$	0.1	0.300	$\frac{9}{16}$	$\frac{11}{16}$	$\frac{13}{16}$	....
	RB-12	$\frac{1}{2}$	0.1	0.300	$\frac{7}{8}$	1	$\frac{27}{32}$	....
	RB-13	$\frac{1}{2}$	0.1	0.750	$\frac{15}{16}$	$1\frac{5}{16}$	$\frac{29}{32}$	....
	RB-14	1	0.1	4.0	$2\frac{1}{16}$	$2\frac{3}{16}$	$1\frac{5}{32}$	....
Screw terminals (Fig. 3·12*b*)	RB-20	$\frac{3}{4}$	1.0	0.450	$\frac{15}{16}$	$1\frac{1}{16}$	$\frac{5}{8}$	$1\frac{3}{4} \pm \frac{1}{16}$
	RB-21	1	1.0	0.800	$\frac{15}{16}$	$1\frac{5}{16}$	$\frac{5}{8}$	$2\frac{1}{8} \pm \frac{1}{16}$
	RB-22	1.5	0.1	1.250	$1\frac{13}{16}$	$1\frac{15}{16}$	$\frac{7}{8}$	$2\frac{7}{8} \pm \frac{1}{16}$
Sealed-in-glass type (Fig. 3·12*c*)	RB-30	1	1.0	0.300	$2\frac{1}{8}$	$2\frac{1}{4}$	$\frac{3}{4}$	....
	RB-32	1	300,001	0.800	$2\frac{3}{4}$	$2\frac{7}{8}$	$\frac{3}{4}$	....
Single-ended bobbin type (Fig. 3·12*d*)	RB-40	0.4	0.1	0.150	$\frac{31}{32}$	$1\frac{7}{64}$	...	....
	RB-41	0.5	0.1	0.300	$1\frac{7}{32}$	$1\frac{7}{16}$	...	....
	RB-42	0.6	0.1	0.450	$1\frac{1}{2}$	$1\frac{3}{4}$	...	....
Small axial-lead type (Fig. 3·12*e*)	RB-51	$\frac{1}{4}$	0.1	0.100	...	...	...	....

Little need be said here concerning the meter resistors; their specifications are almost identical with those of JAN-R-26 for ferrule-terminal power resistors, except that no wattage rating is given for the meter resistors since they are intended for operation at a uniform current of 1 ma for all types, and their resistance tolerance is ± 0.5 per cent. The specifications of JAN-R-93 are roughly similar to those of JAN-R-26 but are somewhat less rigorous mechanically and more rigorous electrically. They will be discussed in more detail in Secs. 3·7 and 3·8.

Most of the accurate resistors made by the various manufacturers are similar to the JAN types, but there are a few other types of interest. Several manufacturers offer bobbin-wound resistors with one or more intermediate taps. Several also make accurate resistors with higher power ratings, both in the form of bobbin-wound units designed and treated for operation at higher temperatures than the usual 105°C and in the form of small power-type resistors with close tolerances on resistance and temperature coefficient. Such resistors are available in ratings

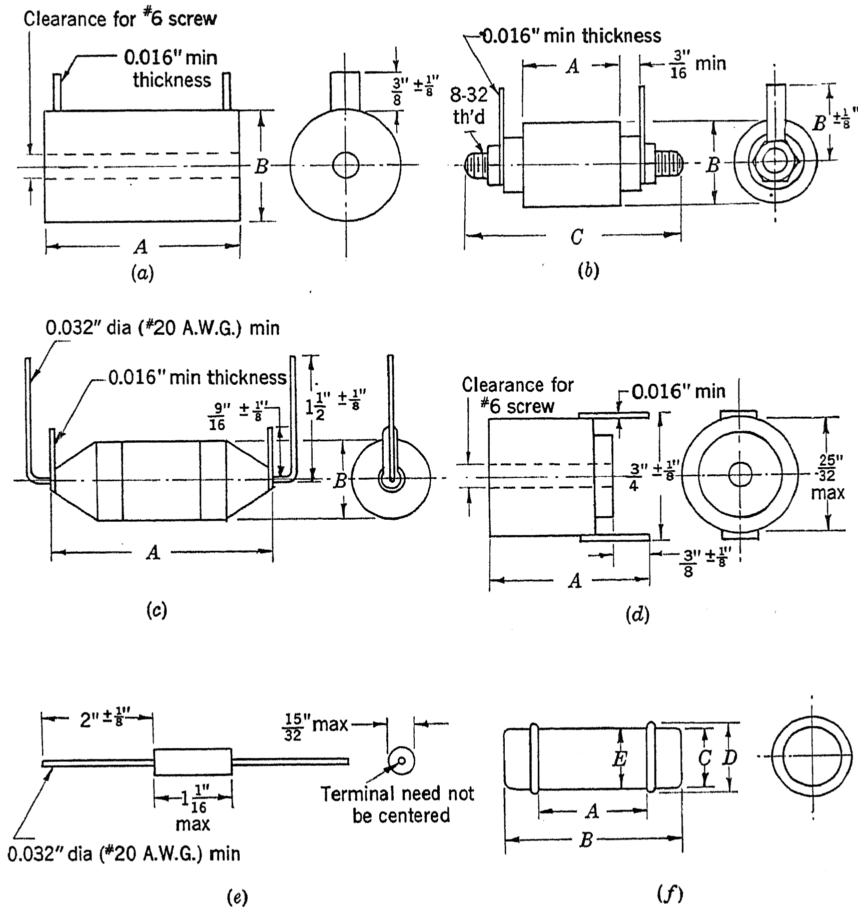

FIG. 3·12.—Dimensions of accurate wire-wound resistors.

TABLE 3·12.—EXTERNAL METER RESISTORS
(High-voltage, ferrule-terminal type, per JAN-R-29)

Type	MFA	MFB	MFC
Resistance, megohms	3.5, 4.0, 5.0, 6.0	1.0, 1.5, 2.0, 2.5, 3.0, 3.5	0.5, 0.8, 1.0
Dimensions, in.	A, max. $8\frac{11}{16}$	$4\frac{3}{16}$	$1\frac{25}{32}$
	B, $9\frac{25}{32} \pm \frac{1}{32}$	$5\frac{9}{32}$	$2\frac{15}{16}$
	C, $1\frac{9}{64} \pm \frac{1}{64}$	$1\frac{9}{64}$	$\frac{13}{16}$
	D, $1\frac{25}{64} \pm \frac{1}{64}$	$1\frac{25}{64} \pm \frac{1}{64}$	$1 \pm \frac{5}{64}$
	E, $\frac{13}{16}$ to $1\frac{5}{16}$	$\frac{13}{16}$ to $1\frac{5}{16}$	$\frac{11}{16}$ to $1\frac{5}{64}$

NOTE: No power dissipation ratings specified. All units operate at 1-ma maximum current. Resistance tolerance ±0.5 per cent. See Fig. 3·12*f* for outline drawing.

up to 10 watts. Resistor units and resistive networks may also be obtained in various enclosures including plug-in types.

The numerous forms of precision resistor that have been developed by the manufacturers of measuring and test equipment will not be discussed here.

3·7. Construction.—Accurate wire-wound resistors are wound on small bobbins of molded plastic or ceramic material. Except in the smallest sizes the windings are distributed among several slots, and usually the direction of winding is reversed in each successive slot in an effort to reduce the inductance of the unit. Such a practice is effective only at comparatively low frequencies because of the leakage flux between slots and the high distributed capacitance in the random-wound sections.

Because of the low operating temperatures, insulated wire is always used for the windings of accurate resistors. Enamel, Formex, and Formvar insulations are the most common, but textile wrappings such as silk, Fiberglas, and resin-impregnated Fiberglas are also used. The resistance alloys are the same as those used for power-type resistors, except that Manganin is also used for the lower resistance ranges. Manganin has a restricted operating temperature range (+10 to +40°C) and is somewhat more difficult to handle than some of the other alloys; its principal advantage is its low thermal electromotive force against copper. Nichrome V is most commonly used for resistance values above 100,000 ohms and also for lower values when a very low temperature coefficient is not required. When the coefficient must be low, Advance or Manganin are usually chosen. A new alloy (Evanohm, produced by the Wilbur B. Driver Co.) has recently appeared which combines the high resistivity of Nichrome V (675 ohm per circular mil foot) with the low temperature coefficient of $25 \times 10^{-6}/°C$. It is a nickel-chromium alloy with a special metallurgical treatment and will soon be in general use.

JAN-R-93 specifies the minimum permissible wire diameter as 1.5 mils for the copper-nickel and nickel-chromium alloys, and 2.0 mils for all others. "All others" in this case is intended to mean Manganin, which is brittle and comparatively weak. Commercial resistors may be obtained with wire as small as 0.8 mil.

After winding, resistors are impregnated with various materials to exclude moisture and to protect the windings mechanically. Before the war, impregnation with any of the usual electrical varnishes was considered sufficient, and some manufacturers used only a wax dip. With the imposition of military requirements for operation at high humidity and over a wide temperature range the prewar treatments were found to offer wholly inadequate protection in most cases, and a number of new impregnants and processes were developed. These processes are now used on practically all units, and afford complete protection against all

but the most severe conditions. For the maximum protection, units are hermetically sealed in glass or ceramic tubes, as in JAN types RB-30 and RB-32 and the meter resistors, or in metal containers with soldered glass bushings. JAN-R-93 establishes two types of protection: Characteristic A resistant to 5 cycles of the salt-water-immersion test (between 0° and 85°C), and Characteristic B to 10 cycles of the humidity test.

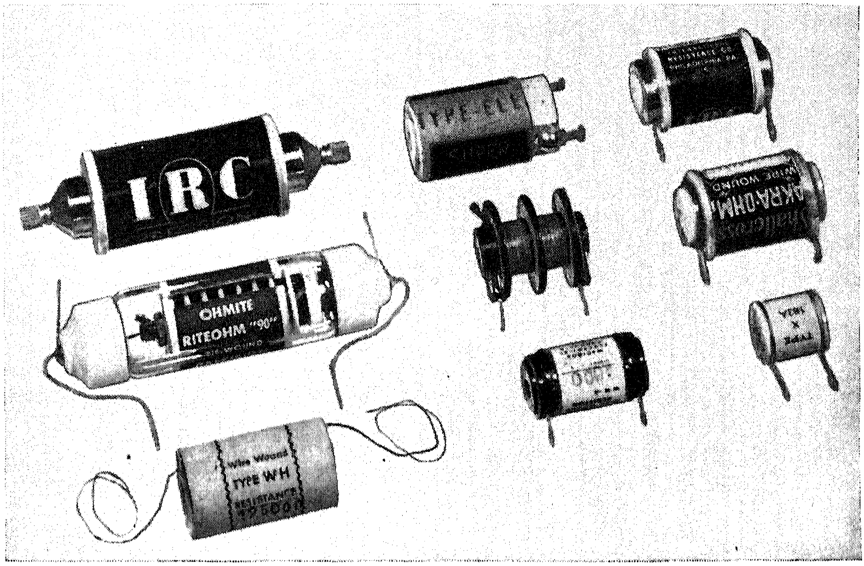

FIG. 3·13.—Typical accurate wire-wound resistors.

Accurate resistors may be furnished with any of a number of terminal types: screw or binding-post terminals, ferrules, soldering lugs, mounting ears, or solid or stranded wire leads. They are usually mounted either by a screw through an axial hole or in fuse or grid-leak clips. Screw-mounting resistors should never be mounted in direct contact with a metal bracket or mounting plate; a bakelite or fiber cushioning washer should always be used between the bobbin and the mounting plate to prevent cracking of the brittle ceramic form. Figure 3·13 shows a group of typical accurate wire-wound resistors.

One type of resistor that has been developed too recently to find its way into the JAN specifications but that meets all the JAN tests and has Navy approval is the Daven Seald-ohm, shown in Fig. 3·14. Up to four resistor units, either bobbin- or card-type, are enclosed in a small drawn-metal case furnished with glass-insulated solder-seal bushings, the case is then filled with a high-melting-point wax, and the bottom is soldered on.

3·8. Electrical Characteristics. *Resistance Values.*—JAN-R-93 lists only maximum and minimum values for the resistances of the various

styles of accurate wire-wound resistor, and all but a very few of the manufacturers do the same for their commercial units. The reason for this is that it would be impracticable, because of the narrow tolerances permitted with this type of resistor, to stock resistors of enough different resistance values to cover the whole range. Consequently these units must be made up and sold on a special-order basis. Some manufacturers do list standard values, the values themselves and the number of nominal values per decade being approximately the same as those listed for the more popular styles of power wire-wound resistors. The JAN resistance ranges are given in Table 3·11. Commercial resistors can be obtained in resistances up to several times the JAN maxima, when smaller wire than the JAN 1.5-mil minimum is used.

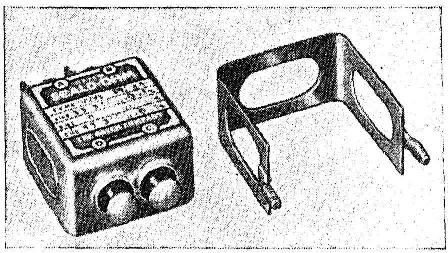

FIG. 3·14.—Daven Seald-ohm resistor unit and bracket. (The soldering lugs on the front terminals were removed by the retoucher; the tips of the rear lugs can be seen above the case.)

The meter resistors of JAN-R-29 are made in eleven standard values corresponding to the ranges of JAN-standard 1-ma voltmeters; some manufacturers also furnish higher and lower values in the same construction.

Resistance Tolerance.—The standard resistance tolerances of JAN-R-93 are ± 0.25 per cent (Tolerance C), ± 0.5 per cent (Tolerance D), and ± 1.0 per cent (Tolerance F). The meter resistors are made to a standard tolerance of ± 0.5 per cent. Commercial resistors are usually made to one or another of the above three tolerances, although several styles are made with a tolerance of ± 2 per cent and special-order resistors can be obtained with tolerances of ± 0.1 per cent, and even as low as ± 0.02 per cent in certain values and constructions. Such extremely close tolerances are justified only in special cases; even with the lowest temperature coefficients available, the resistors and their associated equipment should be temperature-controlled, and great precautions should be taken to avoid extraneous effects such as thermal electromotive forces. In specifying close tolerances for low-value resistors it should also be borne in mind that unless special precautions are taken the resistance of the leads and wiring to the resistor may easily be as much as several

per cent of the resistance of the resistor, thus rendering useless the close tolerance of the resistor itself.

Dissipation Rating.—The power ratings given in Table 3·12 are based upon a maximum hot-spot temperature of 105°C and specified from an ambient temperature of 85°C. Most of the data published by manufacturers gives wattage ratings based on a 30° to 40°C rise over ambient, so that correspondence of ratings is not obtained in many cases. It is necessary to reduce the rated dissipation for resistors supplied in tolerances of better than 1 per cent. The permissible rating for a ± 0.5 per cent resistor is 75 per cent of the rating of a ± 1 per cent resistor; for a ± 0.25 per cent resistor, it is 50 per cent.

Voltage Rating and Insulation.—Because of the high resistance values possible in the precision-type resistors it is obvious that a voltage limitation may be reached before the wattage dissipation limit is exceeded. Particularly with wire sizes smaller than 1.5 mils care must be taken to check the manufacturer's voltage rating in the higher values. In JAN-R-93, a short-time overload test is specified in which a d-c voltage calculated for twice the rated wattage (not to exceed twice the rated maximum voltage) is applied for 10 min. The allowable change in resistance after the test is not to be greater than 0.5 per cent; if the resistor tolerance is less than 0.5 per cent, the change should be no greater than the tolerance. Following this, a 1-sec flash test is given in which the applied voltage is calculated for three times the wattage, except that it is not to exceed twice the rated maximum voltage. This test must not cause arcing, burning, or charring of the insulation. The insulation resistance and breakdown tests on precision resistors are made in a manner similar to that for the power-type resistors. A test potential of 500 volts rms is applied for 1 min between the resistor terminals connected together and the mounting hardware on a V-block. The resistor must withstand this voltage without evidence of insulation breakdown, flashover, or change in resistance. The insulation resistance is measured with a d-c voltage of 100 volts applied as described for the breakdown test. The specification requires that the insulation resistance be not less than 100 times the nominal resistance value in megohms divided by the resistance tolerance in per cent, and in no case less than 50 megohms.

In using precision resistors it is necessary to recognize that they are not able to withstand high voltage with respect to grounded surfaces on which they may be mounted. It is recommended that supplementary insulation be provided if the potential at one of the terminals is more than 250 volts different from ground.

Temperature Coefficient and Stability.—Although the wire alloys used for resistors may be reasonably uniform in temperature coefficient, the temperature coefficient of the finished resistors will vary from unit to

unit because of variations in the winding tension and the resultant irregularity of strains in the metal. Coatings applied to the surface of finished resistors constrict some wire turns more than others and allow irregular physical expansion, which also affects the temperature coefficient. The net temperature coefficient and resistance stability are also dependent to a considerable extent on the physical properties of the bobbins or forms on which the wire is wound. Thermal expansion of the form produces very high pressures in a constrained winding which will upset careful original annealing of the wire.

The effects of strains introduced during the winding process can be almost completely overcome by thermal and current aging of the windings. This is most effectively done by actually passing current through the wire at an ambient temperature of about 100°C. The current used is about twice the normal maximum current for the particular resistance value. This technique removes the strains put in by the winding process and results in a high degree of stability in a very small fraction of the time required by thermal aging alone. After such treatment, one can expect a precision resistor of careful manufacture to retrace to 10 to 50 parts per million over repeated temperature cycles between 0° and 80°C. Over a long period of time a properly aged precision resistor will be stable to ± 0.1 per cent.

Actual measurements on four 1-megohm 1 per cent precision resistors from four manufacturers showed retrace characteristics on cycling between $-20°$ and $+70°$C of about 280 parts per million. The temperature coefficients varied somewhat among the four resistors but this variation was considerably less than that of the resistance values themselves.

Alternating-current Characteristics.—Much of the information in Sec. 3·5 on the a-c characteristics of power-type resistors is also applicable to the bobbin-wound types. In general, the reversal of windings in alternate slots of the grooved form is not as effective in reducing the inductance as is the use of an Ayrton-Perry winding. Furthermore, the depth of winding in the slots and the relatively large number of turns results in higher distributed capacitances than are found in the single-layer power-type resistors. Above about 50 kc/sec, the capacitive effect is pronounced and, in fact, leads to the conclusion that reversal of the windings in alternate slots has little effect on the over-all performance of the resistor at the higher frequencies. For frequencies up to several megacycles per second, the spool type of winding is replaced by Ayrton-Perry windings on mica cards. Obviously, the maximum value of resistance obtainable with this form is considerably less than for the spool type of the same physical size.

Table 3·13 gives the results of some measurements of the high-frequency properties of 1000- and 100,000-ohm bobbin-type resistors

from five different manufacturers. It can be seen that such resistors are unsatisfactory at frequencies of 1 Mc/sec and higher.

TABLE 3·13.—HIGH-FREQUENCY CHARACTERISTICS OF BOBBIN-TYPE RESISTORS*

Manufacturer	Freq., Mc/sec	1000-ohm resistors		100,000-ohm resistors	
		R_{eff}, ohms†	X_{eff}, ohms,†	R, ohms	Shunt capacitance, $\mu\mu$f.
A	1	4,700	−278	85,000	14
A	10	93	−390	5,000	12
B	1	914	+2550	132,000	3
B	10	161,000	res.‡ at 6.5 Mc/sec	14,200	2.8
C	1	990	−44	73,000	2
C	10	830	−341.5	25,500	1.4
D	1	1,090	+2960	14,800	2
D	10	92,000	res.‡ at 4 Mc/sec	24,000	2.3
E	1	1,120	+1600	97,000	3.2
E	10	44,000	res.‡ at 6 Mc/sec	14,200	3.2

* Data from Mr. Leon Podolsky, Research Engineer, Sprague Electric Co., North Adams, Mass.

† $R_{\text{eff.}}$ and $X_{\text{eff.}}$ are the effective series resistances and reactances at the frequency of measurement.

‡ Res. = Resonates.

SPECIAL-PURPOSE AND MISCELLANEOUS RESISTORS

A "general-purpose" resistor, as the term is used in this chapter, is a resistor closely resembling a "standard" resistor, which conforms to one or another of the JAN specifications. Such general-purpose resistors differ from standard resistors only in minor respects, such as inability to withstand the salt-water-immersion or other tests, or in having nonstandard resistance values, temperature coefficients, or dimensions. General-purpose or standard resistors will be found suitable for at least 99 per cent of all applications in electronic equipment, but for the special applications a number of special resistors have been developed. The following sections will briefly describe some of these special-purpose resistors.

3·9. High-voltage Resistors.—A number of types of resistor have been developed for use as bleeders, voltmeter multipliers, and surge resistors in high-voltage circuits such as X-ray power supplies. For some purposes these resistors need not be particularly stable or constant in resistance value, but for voltage or other measurements the requirements are more stringent.

The greatest stability is obtained by the use of wire-wound resistors, and several manufacturers list wire-wound high-resistance units for high-

voltage uses. Sprague, for example, lists the 150-watt type 150F, which is a glass-enclosed ferrule-terminal unit $11\frac{1}{2}$ in. long, rated up to 10 kv between terminals. The standard tolerance is 5 per cent; the resistance may be as high as 100,000 ohms for the noninductive (Ayrton-Perry) type 150 NIF, or 300,000 ohms for the 150F with a progressive winding. Shallcross also lists a 150-watt unit, type 290, which is a $20\frac{1}{2}$-in. single-layer resistor with 1 per cent tolerance, available in resistances up to 3 megohms. It has a heat-resistant lacquer finish and is rated for operation at temperatures up to 175°C; the glass-enclosed Sprague resistors can be used up to 250°C. For lower currents at high voltages Shallcross offers a somewhat less rugged type, consisting of a number of bobbin-type resistors mounted within a spun aluminum corona shield 10 in. in diameter. The shield prevents the formation of corona, with its deteriorating effect on the resistors and the errors caused by the flow of corona current through the resistors, and greatly reduces the electrostatic precipitation of dirt and the resulting leakage. A number of these units can be stacked and connected in series for the measurement of high voltages. Resistances are either 5 megohms ± 0.1 per cent or 10 megohms ± 0.1 per cent; operating voltages are 5 or 10 kv per unit.

For applications in which the resistance required is higher than is practicable to obtain with wire-wound units, composition resistors must be used, and there are several such on the market. The IRC MV and MP series are typical; they consist of ceramic tubes 3 to $18\frac{1}{2}$ in. long, fitted with lug, ferrule, or other terminals and coated with a thin film of resistance material, with a heavy protective varnish coat over all. The MP units have a continuous coating and therefore are good up to high frequencies; the MV units are similar except that they have a small inductance because the resistance material is applied in the form of a spiral band. Standard tolerances are ± 15 per cent; resistances range up to 6 megohms for type MPR and to 20,000 megohms for type MVR. Operating voltages may be as high as 50 kv per unit for the 35-watt $10\frac{1}{2}$-in. type MVO; dissipation ratings run from 4 to 100 watts for the five sizes.

A carbon resistor of construction radically different from that of other types is the Sprague Meg-O-Max unit. This is a large high-voltage power resistor, sealed in glass with metal ferrule ends in the same manner as the Grade 1, Class I wire-wound resistors. Figure 3·15 shows the outside appearance and internal construction of this type. It is made of a number of C-shaped carbon-composition pieces strung on a ceramic tube and connected in series. Except at the point of connection each piece is separated from the next by a mica ring. Three sizes are made, with over-all lengths of about $2\frac{15}{16}$, $5\frac{1}{4}$ and $9\frac{3}{4}$ in., and a diameter of about $1\frac{1}{16}$ in. The resistance ranges available run from a few thousand ohms

to a few hundred megohms, depending on length. The wattage ratings are from 5 to 22 watts, depending on length and resistance value. Maximum rms voltage ratings are in the neighborhood of 5, 10, and 17 kv, respectively, for the three sizes, depending on resistance value. Under low-duty-cycle pulse conditions, peak voltages up to about three times the rms ratings are permissible. The Sprague Meg-O-Max resistor is not made to be a precision type, and a unit may change in resistance up to about 2 per cent in normal operation. In the Radiation Laboratory this type has been used mainly in two applications: as a high-voltage bleeder in cathode-ray-tube power supplies, and in high-voltage regula-

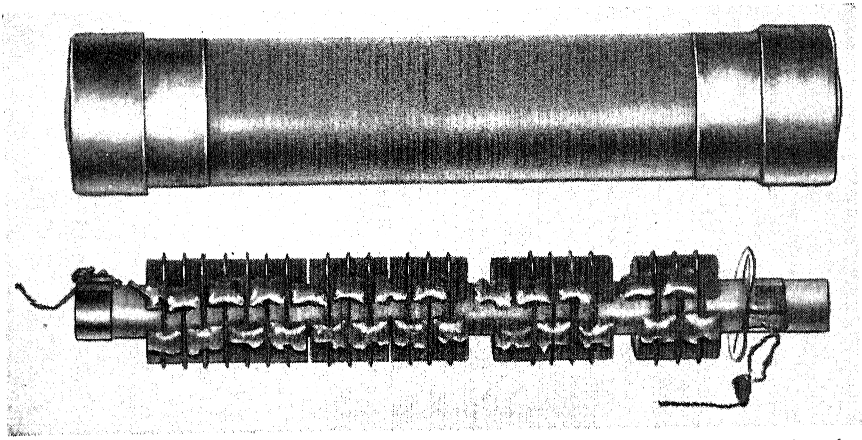

FIG. 3·15.—Sprague Meg-O-Max resistor. (The lower unit was broken in removing the protecting sleeve, and several of the C-shaped resistor elements are missing.)

tors using shunt regulator tubes. In the latter case the voltage divider that feeds the regulator tube grid uses a Meg-O-Max resistor as its upper section and a Western Electric glass-sealed resistor as its lower section. Since the temperature coefficients of these two types are approximately equal, changes of voltage caused by change of divider ratio with temperature are minimized.

3·10. High-stability Composition Resistors.—For many applications, as in electrometer-tube circuits, resistors are required which need not dissipate appreciable amounts of power, but which must have resistance values higher than can be obtained in a reasonable volume with wire-wound types. For most such uses the stability of the resistance is also important. For these applications several types of unit are available. One is the glass-sealed precision resistor of the Western Electric Company, shown in Fig. 3·16. This unit has been used by the Radiation Laboratory in critical parts of range-measuring circuits, chiefly in values between 0.1 and 5 megohms. Its temperature coefficient is nearly constant at different temperatures, with a value between -0.032 and -0.038 per

cent per degree centigrade. For precision voltage-divider purposes these resistors can be obtained in pairs with matched temperature coefficients, so that the ratio between the values of the two units will change less than ten parts per million per degree centigrade. This type is made by depositing resistance material on the outside of a ceramic tube or rod and cutting a spiral groove through the coating so that the current must flow through a long high-resistance path. Glass-sealed resistance units are also made by the Victoreen Instrument Company in values up to 10^{12} ohms, for use in electrometer circuits. The Victoreen units are about $\frac{3}{16}$ in. in diameter and $1\frac{7}{8}$ in. long exclusive of the leads.

S. S. White and International Resistance Corporation also make very high resistance units in several different forms. The S. S. White type 65X 1-watt units are molded in bakelite with axial wire leads and may be obtained in resistance values up to 10^6 megohms. The IRC types FH-1, MG-3, MG-6, and MG-12 are similar in construction to the type F high-

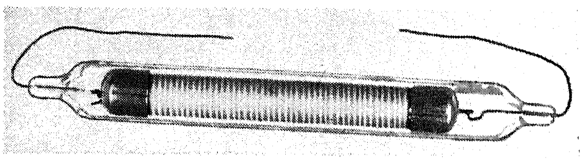

FIG. 3·16.—Western Electric glass-sealed precision resistor.

frequency units described below and consist of glass rods coated with resistance material and enclosed in ceramic tubes, with the ends sealed by alloy castings which serve as terminals. All are $\frac{11}{32}$ in. in diameter, with lengths from $1\frac{13}{16}$ to 12 in. and dissipation ratings from 1 to 8 watts. Maximum voltages are from 500 to 4000 volts, maximum resistances from 10^{10} to 10^{11} ohms, and temperature coefficients from -0.01 to -0.06 per cent/degree centigrade, with the higher values applying to the higher resistances. Standard tolerance is ± 10 per cent.

Two types of resistor of better than ordinary stability are made by the Continental Carbon Company. The type X precision resistor is made in $\frac{1}{2}$-, 1-, 2-, and 5-watt sizes. The range of available resistance values runs from between 1 and 5 ohms to between 1 and 15 megohms, depending on wattage. These units are shown in Fig. 3·17. In many respects Continental Carbon Company precision resistors resemble wire-wound resistors rather than carbon resistors, except that high resistances can be obtained with small size. The temperature coefficient varies from about $+0.01$ per cent per degree centigrade in low values to -0.05 per cent in high values. Resistors of this type are often used in voltage dividers for vacuum-tube voltmeters.

The Continental type A is called a "semiprecision" resistor. The resistor unit is cemented into a glass tube by filling the ends of the tube

with a hard high-melting-point wax. The stability of this unit is not so good as that of type X. Samples measured at Radiation Laboratory had temperature coefficients varying with resistance value from -0.02 to -0.04 per cent per degree centigrade. These resistors are made in $\frac{1}{2}$- and 1-watt styles.

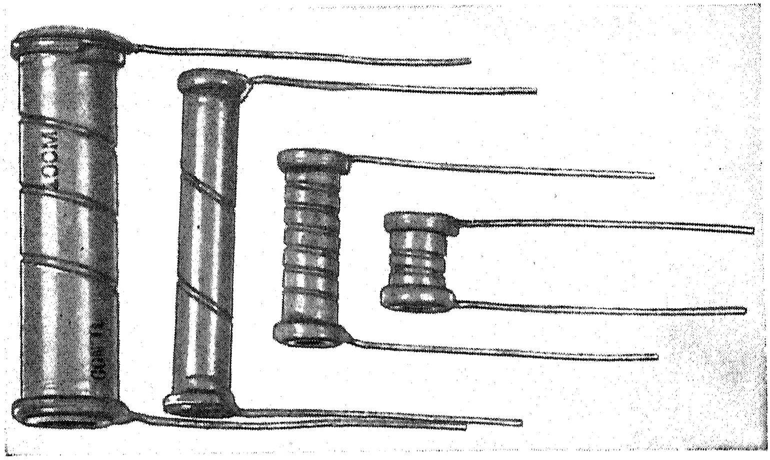

FIG. 3·17.—Continental Carbon Co. precision resistors.

3·11. Metal-film Resistors.—In an effort to produce resistors whose stability would be higher than that of a composition- or carbon-film resistor, several manufacturers have tried sputtered or evaporated-metal films, and two of them have placed such units on the market. One of these is the P. J. Nilsen Company of Oak Park, Ill., whose resistors employ a sputtered film of platinum-iridium or silver-palladium alloy as a resistive element. The film is deposited on a threaded cylindrical porcelain form which is then ground to remove the conducting film from the top of the threads, leaving a continuous metallic spiral. The resistor is thus similar to the Western Electric Company precision unit described above. The ends of the cylinder which serve as terminals, are plated with silver for about $\frac{1}{8}$ in.; a porcelain outer shell with similarly plated ends is slipped over the grooved form; and the whole unit is sealed by dipping the plated ends in solder. Figure 3·18 shows the unit without its protecting shell, and also a complete resistor. The resistance of the unit can be established to an accuracy of ± 0.1 per cent by controlled or hand-finishing of the grinding process. By proper selection of the sputtering alloy and control of the film thickness the temperature coefficient can be

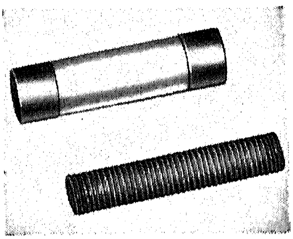

FIG. 3·18.—Nilsen sputtered precision resistor.

varied and controlled when accurate matching is required. Pairs of resistors have been made which match to better than $50 \times 10^{-6}/°C$. The absolute temperature coefficient depends somewhat on the resistance value and the physical size, varying from about $150 \times 10^{-6}/°C$ to slightly negative values. This negative value with a positive-coefficient material has been explained as due to contact-potential effects present in thin films. The voltage coefficient for a 1-megohm resistor is about 2×10^{-6} per volt between 2 and 200 volts. The resistance range in the $\frac{1}{2}$- by 2-in. size of Fig. 3·20 is from 5000 ohms to about 3 megohms. It is possible to obtain values as low as 500 ohms by using an ungrooved cylinder, which also gives a practically noninductive resistor. This size is conservatively rated at 1 watt and may be operated at temperatures from $-40°$ to $+85°C$ without derating.

Another type of metallic-film resistor has recently (January 1946) been placed on the market by the Corning Glass Works, the product of

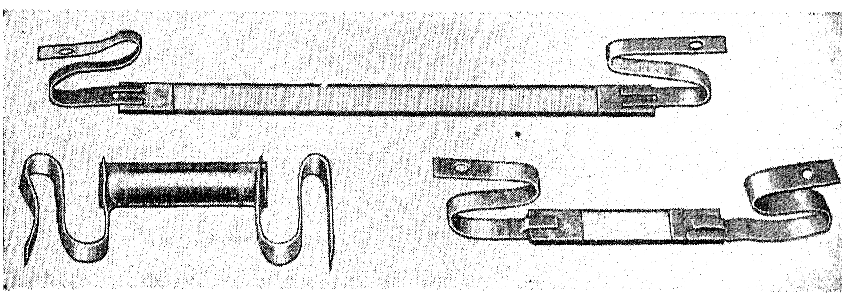

FIG. 3·19.—Pyrex resistors.

joint research by the Corning Glass Works and the Polytechnic Institute of Brooklyn. According to the manufacturer these Pyrex resistors are very stable in spite of the fact that the film thickness is only about 10^{-5} cm. It is thin enough to pass an appreciable fraction of the visible light incident on it; two such resistors showed transmissions of 13 and 50 per cent, including the absorption of the glass and the protecting silicone varnish film. After 1000 hr at maximum power the change in resistance is less than 0.5 per cent. The films themselves are surprisingly resistant to abrasion, and are protected by the silicone coating. Standard tolerances are ± 10 per cent and closer tolerances are available on special order; resistance ranges and other characteristics are given in Table 3·14, and a photograph of three typical units is shown in Fig. 3·19.

3.12. Varistors and Thermistors.—In most applications it is desirable that the resistance of a resistor remain constant under changing conditions, but there are many cases where a resistor could be used whose resistance is a function of some condition such as temperature or applied voltage. Following Western Electric practice, such variable resistors

will be termed *varistors.* Three principal classes may be distinguished: thermistors, which obey Ohm's law but with a large variation of resistance with temperature; symmetrical varistors in which the current-voltage characteristic is nonlinear but is symmetrical about the origin; and unsymmetrical varistors such as the various types of dry-disk and point-contact rectifiers.

TABLE 3·14.—PROPERTIES OF PYREX RESISTORS‡

Property	Form				
	Flat strip $\frac{1}{16}$ in. × $\frac{3}{8}$ in.				Tube $\frac{3}{8}$ in. OD, $1\frac{1}{2}$ in. long
	5 in. long		$1\frac{5}{8}$ in. long		
Resistance range, ohms	200 to 4000	4000 to 100,000	50 to 1000	1000 to 25,000	1 to 500
Temperature coefficient*	+0.02 to −0.02	+0.02 to −0.08	+0.02 to −0.02	+0.02 to −0.08	0.08
Maximum input, watts	12	8	3	2	4
Watts input for rise of,† °C					
40	2	2	½	½	½
80	4	4	1	1	1
130	8	8	2	2	2
170	12	..	3	..	..
230	..	..	..	..	4

* Temperature coefficients in per cent per degree centigrade. They are less than 0.02 per cent for resistances up to 5000 ohms in the $1\frac{5}{8}$-in. strip sizes and less than 0.02 per cent for resistances up to 20,000 ohms in the 5-in. strip sizes.

† Rise above ambient of 25°C.

Voltage coefficients for resistances above 1000 ohms are less than +0.02 per cent volt for the 5-in. and less than +0.06 for the $1\frac{5}{8}$-in. strips; they are not defined for the tubular resistors.

‡ Data from Corning Bulletin EI-P-10, Jan. 18, 1946.

Thermistors.—Devices in which the variation of resistance with temperature is utilized fall into two classes: those in which the resistor element is metallic and those in which it is a semiconductor. The thermal coefficients of most of the pure metals are positive and lie between +0.3 and +0.6 per cent/degree centigrade and are too small to be of much interest except for such specialized applications as resistance thermometry. Iron is a partial exception, since its resistivity changes rapidly over a small range of temperatures near red heat. This has led to its use in the iron-wire-in-hydrogen ballast lamp, which when connected in series with a constant load will keep the current nearly constant over a range of input voltages as great as 3 to 1.

Certain of the semiconductors have coefficients negative in sign and much greater in magnitude than those of the metals. The coefficients of

uranium oxide (U_3O_8), nickel-manganese oxide ($NiO + Mn_2O_3$), and silver sulfide (Ag_2S), for example, are respectively -3.0, -4.2, and -4.9 per cent/degree centigrade. Such large coefficients result in a doubling of resistance for a temperature drop of as little as 20°C. The law relating resistance and temperature is approximately of the form

$$R = R_o e^{\beta[(1/T)-(1/T_o)]},$$

where R_o is the resistance at the reference temperature T_o and T is the actual (absolute) temperature. The "constant" β is strictly a constant for Ag_2S up to 179°C, where a phase change occurs. For the other materials β varies somewhat with temperature, resulting in slightly curved plots of log R against $1/T$.

Resistors with these characteristics are manufactured by the Keystone Carbon Company and the Speer Carbon Company (NTC resistors), by the Globar Division of the Carborundum Company (Globar type B and type D resistors), and by the Western Electric Company (thermistors). Those of the first three companies are similar in appearance and construction to ordinary uninsulated composition resistors. Western Electric thermistors are rods, beads, or plates of sintered oxides or sulfides. Connection is usually made to the beads by embedded platinum wires and to the other forms by sprayed metallic coatings. Rod and disk thermistors may be used unmounted; beads are usually mounted in evacuated or gas-filled glass bulbs; and devices are also available in which one or more thermistors and other associated equipment are mounted in unit assemblies, usually in metal cans.

Thermistor applications may be divided into three main classes. In the first class the current through the thermistor element is too small to cause appreciable heating, and the change of temperature is due to wholly external causes. This class includes the use of thermistors in resistance thermometry, in the bolometric measurement of radiant energy, and in the measurement of microwave power. This last application was of great importance in the work of the Radiation Laboratory, and examples are given in other volumes of this series, particularly in Vol. 11.

As resistance thermometers, thermistors have at least ten times the sensitivity to temperature changes shown by platinum thermometers. Their absolute accuracy is not so high, at least in the present state of the art, but is said to be much greater than that of thermocouples. Thermistors can easily be made to have much greater resistances than either of these devices, which is advantageous in cases where it is desired to couple into vacuum-tube amplifiers. Thermistors can also be made to have much smaller thermal capacities and shorter time constants than conventional resistance thermometers, though they do not as yet approach radiation thermocouples or bolometers in these respects.

Another obvious and useful application in this class is the use of a thermistor to compensate for the positive temperature coefficient of a coil or other device. A thermistor of suitable characteristics may be closely connected thermally with the coil and electrically connected in series with it. As the temperature rises, the coil resistance will increase and that of the thermistor will decrease correspondingly. If compensation over a wide temperature range is desired, it is usually necessary to shunt the thermistor with a Nichrome resistor in order to straighten out its characteristic. This type of temperature compensation has been very useful, for example, in airborne instruments.

In the second class of thermistor applications, the measuring current is again too small to cause appreciable heating, but the change of temperature is caused by heat generated in a resistance heater associated with the thermistor element. Such a heater-type thermistor may have the heater physically separate from the thermistor element or it may consist of a glass-covered thermistor bead with the heater imbedded in the glass. One obvious application of such a separately heated thermistor is as a remotely controlled circuit element. For example, the thermistor element could be used as the shunt element of an attenuator, and the heater fed with a-c or d-c power from a remote point; the greater the heater current the lower the shunt resistance and the greater the attenuation.

A variant of this scheme is a volume compressor or expander in which the output furnishes the heater current and the thermistor is an element of an attenuator in the input circuit. This is a special case of a feedback amplifier in which the feedback is thermal rather than electrical. The time constant of the thermistor can be made sufficiently short to permit following the syllabic variation of speech. Another use for the heater is to furnish ambient temperature compensation for the thermistor element; the heater current is controlled by a disk-type thermistor mounted in the same enclosure. Resistance control with a separate heater may be accomplished with fairly small heater powers; one type of thermistor with a 100-ohm heater had a cold resistance of 1 megohm, which decreased to 8 ohms for a heater input of 20 mw.

In the third class of thermistor applications, the heating is primarily due to the thermistor current itself. This current may be held constant, and the change in resistance with changing external conditions used to measure such quantities as gas flow, thermal conductivity, pressure, or even position. In this last application two thermistor beads in the same gas-filled bulb are connected in adjacent arms of a bridge. If the bridge is balanced when the two beads are in the same horizontal line, a tilt of the bulb will cause an unbalance of the bridge because the upward-moving convective gas streams in the bulb will cause the higher of the two thermistors to reach a higher temperature.

Another group of applications of the third class depends upon the fact that if the power input is changed, the thermistor will come to equilibrium at a new temperature and therefore at a different value of resistance. This property is used, for example, in protective devices for switchboard lamps, etc. If a self-heated thermistor of appreciable thermal inertia is connected in series with a lamp, a momentary surge—even of considerable magnitude—will not heat the cold thermistor enough to drop its resistance to the point where the lamp will burn out while a much lower voltage of long duration will heat the thermistor and permit the lamp to light.

The same scheme is used to prevent false operation of relays. It may also be used to secure time delays in the operation of relays or other devices. With proper design of both the thermistor and the relay, delays can be secured from a few milliseconds to many minutes. In order to secure reasonable constancy of delay, however, it is necessary to compensate for ambient temperature variations, to assure constancy of the applied voltage, and to use a relay with a very constant operate current (see Chap. 13).

If the current through a self-heated thermistor is gradually increased, time being allowed for the attainment of thermal equilibrium after each change in current, it will be found that the voltage drop across the unit will reach a maximum and will thereafter decrease with increasing current, so that the voltage-current curve has a negative slope. Still further increase in current will cause the curve to pass through a minimum and the slope to become positive again. The result is very similar to the dynatron characteristic of a tetrode with a secondary-electron-emitting screen grid, and like it the thermistor can be used as an oscillator. The frequency range possible is limited by the finite thermal capacity of even the smallest thermistor bead, but frequencies throughout most of the audio range can be reached. There would appear to be no theoretical lower-frequency limit.

The negative resistance characteristic permits use of a thermistor as an amplifier or as a switching device, and the fairly sharp kinks in the characteristic suggest its use as a modulator or demodulator. These possibilities have been comparatively little explored, but the device does make a useful volume limiter and a very good output stabilizer for oscillators. When combined with constant series and/or shunt resistors, it also serves as a voltage regulator. Thermistors are still relatively new, and their uses will undoubtedly multiply greatly in the future.

Symmetrical Varistors.—Symmetrical varistors are resistors whose resistance is independent of the direction of the applied voltage but depends upon its magnitude. They are manufactured by the Globar Division of the Carborundum Company (Globar Type BNR voltage-sensitive resistors), Metropolitan Vickers, Ltd. (Metrosil resistors),

Western Electric Company (silicon carbide varistors), and General Electric Company (Thyrite resistors). For convenience they will be referred to by the General Electric trade name.

Thyrite resistors are made by pressing specially treated silicon carbide with a ceramic binder into shapes and firing at about 1200°C. Their properties are very sensitive to variations in the process of manufacture, so that the finished resistors are somewhat variable in characteristics. (Two pairs of supposedly identical but not especially selected units showed characteristics that were the same within 5 per cent in voltage.) After firing and attaching terminals, the rather porous units are impregnated to prevent water absorption.

The conductivity of a mass of Thyrite is uniform in all directions but rises very rapidly with applied voltage. The material may be thought of as an aggregate of resistive granules separated by minute gaps insulated by films of silicon dioxide. The higher the potential gradient the larger the number of these gaps that break down and conduct. The insulation reforms immediately after the discharge ceases. The current is thus independent of the polarity and frequency of the applied voltage and depends only upon its instantaneous magnitude.

To the first approximation, the current i through a Thyrite unit can be expressed as a function of the applied voltage E by the equation

$$i = \sigma_1 E^n \qquad \text{(amperes, volts)}, \tag{1}$$

where σ_1 is the conductivity of the unit in amperes at 1 volt applied and n is a constant depending upon the composition of the resistor material. The value of n usually exceeds 3.5 and may be as high as 7; its average value is about 4. Its magnitude is only approximately independent of the applied voltage, so that the current-voltage curves plotted on a log-log scale droop for voltage gradients below approximately 100 volts per inch. With this limitation, however, Eq. (1) holds true over ranges of at least 200 db. Where heat dissipation is a factor, however, the usable range may be reduced to 100 db.

The conductivity of commercial Thyrite, measured as current for constant applied voltage, rises about 0.4 per cent/degree centigrade rise in temperature. This temperature sensitivity is probably accidental rather than an inherent characteristic of the material. Its value varies widely between samples; in a batch tested between −36° and +97°C., the temperature coefficient varied between 0.12 and 1.2 per cent/degree centigrade. Even two strips fashioned from adjacent portions of the same disk differed substantially in their temperature coefficients.

Since it has been fired at a high temperature in the process of manufacture, Thyrite itself is not harmed by reasonable overloads, but its wax impregnation will suffer, and so may the electrodes, which are usually

sprayed-on metal deposits. A dissipation of 0.25 watts per square inch of surface is therefore given as the highest rating.

Thyrite units are made in the form of rods $\frac{1}{4}$ in. in diameter and from $1\frac{1}{8}$ to $2\frac{1}{4}$ in. long and as circular disks from $\frac{1}{2}$ to 6 in. in diameter and from 0.03 to several inches thick. The rods and the smallest disks have pigtail leads; the larger units are intended to be mounted between clamps, either singly or in stacks.

By choosing the appropriate shape and composition, Thyrite units can be adapted to voltages from 0.1 to 10,000 volts and to currents from 10^{-7} or less to hundreds of amperes. They are suitable for applications where moderate nonlinearity is required over wide voltage ranges.

Thyrite has been comparatively little used except for surge and lightning protection, for which it is almost ideally adapted. It offers interesting possibilities as a nonlinear element for multipliers, special waveform generators, etc., and will undoubtedly find many more uses in the future.

Unsymmetrical Varistors.—Unsymmetrical varistors are resistors whose resistance is a function both of the magnitude and of the direction of the applied voltage. Because the resistance is different for different polarities, they can be used as rectifiers. The two most important classes are the point-contact crystal rectifiers, to which Vol. 15 of the Radiation Laboratory Series is devoted, and the dry-disk rectifiers commonly used for battery charging and similar purposes. Crystal rectifiers depend for their action upon the rectifying properties of a fine metallic point, usually of tungsten, in contact with either silicon or germanium. Dry-disk rectifiers depend upon the unilateral conductivity of the interfaces between copper sulfide and magnesium, copper and cuprous oxide, or selenium and iron or aluminum.

As power rectifiers the copper sulfide, copper oxide, and selenium units have comparable properties, but their individual differences are great enough to make one preferable to another in many applications. The copper sulfide rectifier is the oldest and probably the least popular and is made by comparatively few manufacturers. One of its desirable properties is its ability to withstand high temperatures and high momentary overloads. It is also the cheapest of the three types.

Copper oxide rectifiers are desirable as meter rectifiers because their rectification efficiency remains high at low voltages. They withstand overloads better than selenium but cannot be operated at as high ambient temperatures as copper sulfide. The modern copper oxide rectifier is an economical, dependable, and relatively trouble-free unit and is used in large numbers to furnish direct current for battery charging, electroplating, magnet and relay operation, etc., as well as for low-current applications.

Selenium power rectifiers are newer than either of the other types and

seem to be displacing them for many purposes. They are characterized by high efficiency, good voltage regulation, small change in properties with temperature (except that they cannot be used at as high temperatures), and low weight and compactness in the higher voltage ratings and especially by the high permissible back voltage per plate. This last property is of especial interest in the use of selenium rectifiers in plate supplies. Special high-voltage selenium rectifiers are available with ratings up to 4 kv at 5 ma. Four such units were used in the plate supply illustrated in Fig. 4·19. Larger high-voltage stacks are used in the plate supplies of several radio transmitters now on the market.

Unsymmetrical varistors are useful for a wide variety of applications. Crystal rectifiers are commonly used as mixers, detectors, d-c restorers, etc.; many examples of these uses will be found in the other volumes of this series. Crystals such as the 1N34 can be substituted for thermionic diodes in perhaps 90 per cent of these applications, often with an improvement in performance. The principal weakness of the crystal diode is its finite back resistance, though this may be of the order of some megohms. Crystals and small copper oxide and selenium meter rectifiers are also useful as low-power modulators and demodulators, and matched pairs or sets of crystals are now obtainable for these purposes. Larger rectifier stacks are also useful at higher power levels. The frequencies at which disk-type rectifiers can be used are normally limited to the audio and carrier ranges by their comparatively large interelectrode capacitance.

Beside their uses as rectifiers, both crystals and disk rectifiers are useful as symmetrical nonlinear circuit elements. The required symmetry is easily obtained by paralleling two identical units with their polarities opposed. When so connected, a pair of copper oxide units will have characteristics such that the current increases exponentially with the applied voltage. The lower limit of this exponential characteristic lies at about +70 mv, at a current density of about 50 $\mu a/cm^2$. The upper limit depends upon the application, but a range of 50 to 1 can be obtained if the linear component of the rectifier resistance is canceled out by the use of a bridge circuit.

Certain germanium microwave mixer crystals show this characteristic to an even greater extent, since their forward resistances are very low. Their forward characteristic rises strictly exponentially from the lowest observed point of 1 μa at +160 mv to 10 ma at +500 mv. If the bridge circuit is used, this exponential range can be extended to as much as 300 ma per contact.

Selenium rectifiers have a characteristic consisting of two approximately linear portions connected by a sharp bend. They thus have a highly nonlinear characteristic but only over a narrow voltage range. Such a characteristic is useful in a limiter; for example, a pair of

selenium elements connected back to back makes an excellent limiter for shunting a pair of headphones used with an a-f bridge.

When used in the back-to-back connection, the various rectifiers form a useful complement to Thyrite, having their field of application at voltages below about 1 volt where Thyrite begins to fail.

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3·13. Wire-wound R-f Resistors.—Although most wire-wound resistors have residual inductances and capacitances too large to permit their use as accurate circuit elements at radio frequencies, there are certain forms that can be used up to fairly high frequencies. The a-c properties of Ayrton-Perry windings have been discussed in Secs. 3·5 and 3·8; other windings such as the Figure 8 and even more complicated configurations have been devised which give even better characteristics, but most of them are too difficult to construct to be practical in any application except special measuring and test equipment.[1]

There are certain commercially available resistors which have fairly good high-frequency properties. Two such types are the Ohmite Models D-100 and D-250, which have noninductive space-wound wire resistance elements, supported on skeleton mica forms in sealed gas-filled bulbs with connections brought out to four-prong vacuum-tube bases. The D-100 is available in 13 resistance values from 13 to 600 ohms with 100-watt dissipation ratings. Distributed capacitances are approximately 5 $\mu\mu$f for all values; residual inductances range from 0.19 to 1.0 μh. The frequencies at which the impedance increases 10 per cent vary from about 5 Mc/sec for the 13-ohm unit to about 40 Mc/sec for 600 ohms. The larger Model D-250 has similar characteristics except for its dissipation rating of 250 watts. Resistance tolerance is ± 5 per cent for both models.

Another high-frequency power resistor is the Ward Leonard placque unit. This is a flat vitreous enameled unit, $\frac{1}{2}$ in. thick, with a zigzag winding covering a rectangular area in a depression in the form. Three sizes are available, with ratings of 20, 40, and 125 watts and resistances

[1] B. Hague, "A-c Bridge Methods," Pitman, London, 1943, pp. 86–127.

from 0.64 to 25,000 ohms. The maker states that they show no standing waves below 60 Mc/sec, that inductive effects are negligible up to 1 and capacitive to 5 Mc/sec; changes in effective resistance are negligible to 7, 3, and 0.2 Mc/sec for the small, medium, and large sizes, respectively.

A type of winding that is often used for heaters but which is nonreactive enough for use up to several megacycles per second is resistance cloth. It consists of a textile warp, of cotton or other organic fiber in low-power types and of asbestos or Fiberglas cord in the higher powers, into which is woven a weft of resistance wire or ribbon. Such a winding has very low inductance and capacitance and has been much used in the construction of dummy loads for broadcast and other radio transmitters. Because the whole area of the resistance wire is exposed to the air the dissipation of heat is excellent and if the material is oil-immersed or cooled by an air blast high powers can be dissipated. Under the name of Ohm-Spun the material is sold for applications such as oven heaters; a lower-temperature type in the form of a 1-in. continuous tape is used for a-c resistance standards of values higher than can conveniently be obtained in Ayrton-Perry cards. A coil of such material with a resistance of about 25,000 ohms is only about an inch in diameter and has negligible inductance up to the carrier-frequency range; distributed capacitance can be minimized by interwinding the tape with a corrugated insulating spacer.

Another material of similar properties is resistance cord, which may be any of various types of continuous core over which is wound a continuous coil of resistance wire. Such resistance cord is used in making electric heating pads, soil-heating cable, etc. For these uses it usually takes the form of bare Nichrome space-wound on a heavy soft asbestos cord. Wound on enameled magnet wire with a heavy asbestos wrapping and the whole wound on a threaded ceramic form, it was used in the old Electrad resistors; these units were greatly inferior to present-day power resistors in some respects, but had the advantage of being easy to tap accurately, so that accurate resistance values could be made up by the user. One form of Electrad resistance cord, which was wound in a silk core about $\frac{1}{16}$ in. in diameter, had a resistance of as much as 15,000 ohms per ft. Small lengths of resistance cord enclosed in insulating braid sleeving and terminated by tinned wire leads are often used for cathode resistors for small tubes; one of their advantages is that they can easily be coiled or bent to fit almost any space. Resistance cord has very low inductance because of the small area of the core; the capacitance depends upon the configuration into which it is bent or coiled.

3·14. High-frequency Resistors.—Resistors intended for use at high frequencies are usually designed to have one or more of the following properties:

1. Low direct end-to-end capacitance.
2. Low total capacitance.
3. Small change of resistance with frequency.
4. Low inductance.

In the frequency range up to 100 Mc/sec the first three properties are of interest in resistance values above about 500 ohms and the fourth in values below about 50 ohms. In the intermediate resistance range some suitable type of general-purpose resistor can usually be found.

The IRC filament-type resistors without the leads projecting inside the unit have good high-frequency qualities in the high-resistance category. Type F shows much less resistance change at high frequency

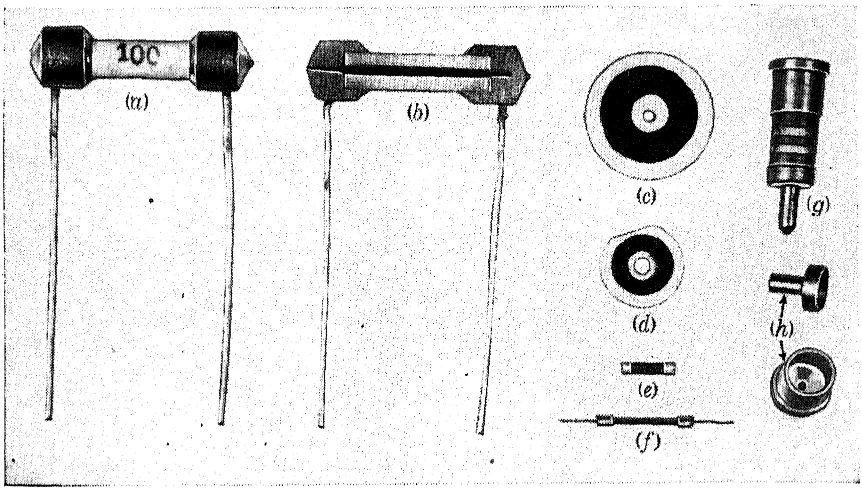


FIG. 3·20.—High-frequency resistors: (*a*) IRC type F; (*b*) IRC type F (longitudinal section); (*c* and *d*) two types of IRC disk resistors; (*e*) small Globar unit; (*f*) MPM resistor; (*g*) dummy-crystal unit; (*h*) metal parts for dummy-crystal unit.

than ordinary resistors, and the new type MPM has unusually low direct end-to-end capacitance. Its resistance is said to change even less than that of type F. Resistors of type F, because of their bulky end caps, are not suitable where low total capacitance is desired (see Sec. 2·8). Both types are shown in Fig. 3·20*a*, *b*, and *f*. Somewhat more specific information on their high-frequency properties is given in Sec. 2·8.

An example of a particular high-frequency resistor is also shown in Fig. 3·20*g* and *h*. When radar receivers are being developed and tested, the intermediate-frequency test signal must be introduced through a "dummy mixer" to make the i-f input circuit act as it would if a real mixer were feeding it. The dummy mixer often is made by modifying a real mixer, by substituting a resistor in the place of the rectifying crystal. The "dummy crystal" resistor is made to have the same

mechanical dimensions as a regular silicon rectifier unit by fitting suitable end caps onto it and soldering them to the leads, which are threaded through holes and cut off short. General-purpose RC-20 resistors of about 300 ohms are used in making up these dummy crystals. More information on the use of these units is given in Vols. 18 and 23 of the Radiation Laboratory Series.

Some types of resistor are especially useful in high-frequency wide-band equipment because their small size allows them to fit into the compact miniature type of layout which is often required in such equipment. The Globar 997-A is an example of a type used in such cases where insulated resistors were not required. Another very small Globar type, used in some experimental microwave devices, is shown in Fig. 3·20*e*.

3·15. Ultrahigh-frequency Resistors.—Resistors of very low reactance find application particularly in the microwave region. An interesting example of microwave resistors is the resistor disk, two samples of which are shown in Fig. 3·20*c* and *d*. These are made by IRC from their resistor sheet material, which is itself of interest. Resistor sheet material consists of a sheet of low-loss phenolic plastic coated with a layer of resistive material. A square of this material will have the same resistance from the whole length of one edge to the whole length of the opposite edge no matter what its size, so the specific resistance of this type of material is figured in terms of ohms per square. It is available in strips up to 3 in. wide and in specific resistance values of 100, 200, 300, 400, 500, and 600 ohms per square. Reliable contact can be made to it only by painting part of its surface with a metallic coating, but in some microwave applications pieces of resistor-sheet material are simply placed in an electromagnetic field, outside connections being unnecessary. The resistor disks of Fig. 3·20*c* and *d* are used as low-inductance shunt resistors in coaxial lines carrying microwave energy. For instance, disks having a resistance equal numerically to the characteristic impedance of the line are often built into devices which are connected to such a line. These disks form part of arrangements which terminate the line and thus minimize reflections. They are painted with an outer and an inner metal ring to make connection with the two conductors of the cable, and have a hole punched in the center. Contacts are made by pressure on the metal-painted surfaces, using mechanical parts that screw together squeezing the disk between them. If the inner diameter of the outer metallic ring is r_2, the outer diameter of the inner metallic ring, r_1, and the specific resistance S, then the resistance from center to rim of the disk is given by

$$R = 0.367S \log_{10} \frac{r_2}{r_1}.$$

It is easy to show that if the resistance of a coaxial disk is to match the impedance of a certain air-dielectric transmission line, and if r_1 and r_2 of the disk are to be the same as the corresponding radii of the coaxial line itself, then the specific resistance of the sheet material must be 376.6 ohms per square, a value numerically equal to the impedance of free space. Resistance sheet material is used in many ways in microwave equipment using waveguides as well as coaxial lines. Some of its applications are described in Vols. 11 and 16.

Another special low-inductance resistor, used at video frequencies, is the coaxial pulse-current viewing resistor. When the shape of a large current pulse, such as the current in a transmitting magnetron, is to be observed, it is necessary to convert it into a voltage pulse for presentation on the cathode-ray tube of an oscilloscope or synchroscope. This is done by putting a low-value resistor in series with the circuit at its grounded end, and observing the voltage pulse built up by the current through the resistor. The value of the resistor is low enough to be negligible compared to the rest of the virtual resistance of the circuit, and acts somewhat like an ammeter shunt. An ordinary resistor has sufficient inductance so that when the current pulse starts the series resistor has momentarily a much higher impedance than normally, and a high spike appears at the front edge of the picture of the pulse. Two means are used for reducing the spike in this special resistor:

1. Lead inductance effect is minimized by making the resistor a three-terminal device. The ungrounded lead runs through the center of the resistor, and the voltage pulse is picked off at the opposite end from the one at which the current pulse enters.

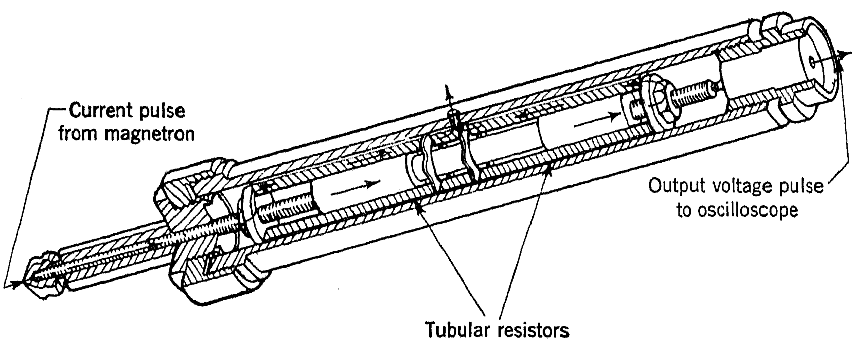


Fig. 3·21.—Coaxial pulse-current-viewing resistor showing paths of current flow.

2. Inductance of the resistor itself is minimized by arranging the current paths so that the magnetic fields almost completely cancel out. The whole unit is built in cylindrical form, and its resistive portion consists of a pair of tubular ceramic resistors furnished by

Bell Telephone Laboratories, (BTL ES-720916 and ES-720917). The current paths in this device are shown in Fig. 3·21. Resistance values ordinarily used in this resistor range from 1 to 10 ohms. The inductance is low enough so that a reasonably accurate picture is presented of a pulse of many amperes which rises in about 0.01 μsec. More detailed information on the use of these devices is given in Appendix A of Vol. 5 (Pulse Generators).

Constructions similar to that used in the pulse-viewing resistor have also been used in other resistive devices for use at ultrahigh-frequency. Cylindrical film-type resistors have been employed in a number of terminating impedances for both coaxial lines and waveguides; the dissipation ratings have ranged from a watt or so in low-level test equipment up to several kilowatts in a water-cooled 10-cm termination for $1\frac{5}{8}$-in. coaxial lines which has recently been developed by the International Resistance Corporation.

CHAPTER 4

IRON-CORE INDUCTORS

BY J. F. BLACKBURN AND S. N. GOLEMBE

From the standpoint of the circuit designer, transformers and other iron-core inductors occupy a place somewhat apart from such components as fixed resistors or capacitors. Units of the latter types are available in an almost embarrassing profusion, and about all that a circuit or apparatus man needs to know about them is their electrical and mechanical characteristics and their construction. In the case of transformers, however, although there are on the market many stock sizes and types that will satisfy most ordinary requirements, it is frequently necessary to order special units. In order to do so intelligently, and particularly in order to know whether it is practicable to attain the desired performance, it is important for the circuit designer to have at least a bowing acquaintance with the methods of transformer design and with its possibilities and difficulties.

It would be impossible within the limits of a single chapter to cover the field of transformer design, even in an attenuated form, but in the following section there will be presented a group of useful design formulas, followed by three sections briefly outlining the design procedures for the more important classes of iron-core inductors. Following this design portion of the chapter there are five sections on construction and assembly techniques, with special emphasis on those employed by the transformer shop of the Radiation Laboratory, and descriptions of several units that were designed and built there.

DESIGN OF IRON-CORE INDUCTORS

4·1. Design Formulas.—The design of iron-core inductors, like all types of design, is a process of continual balancing and compromise, and it is rendered more troublesome than many fields of design by a very Babel of conflicting systems of units. In the United States, at least, it is the universal custom to use the English system of linear measurements for wire, insulating materials, and most other components entering into the construction of a transformer except the core. The manufacturers of magnetic materials, however, use both English and metric units, presenting some data in one system and other data in the other. For this reason the formulas that follow will be given in two forms, one

using the practical metric units and the other, a mixed system of units based on the inch.

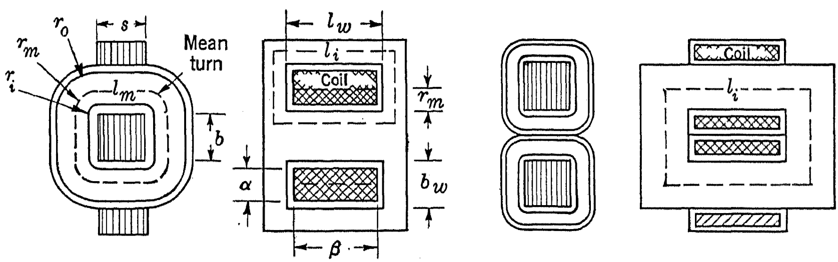
The formulas in this section are not grouped in a particular logical order since each designer has his own preferred sequence of operations in designing an inductor. The formulas are not to be considered as highly accurate because many of them are empirical approximations and because almost all of them are subject to errors due to the inherent inaccuracies in some of the quantities involved. This does not imply that the design of apparatus involving magnetic circuits is necessarily an inaccurate procedure, but rather that the formulas given here are first approximations that can be considerably refined by suitable corrections. As they stand they are sufficiently accurate for most ordinary purposes.

Voltage.—The basic formula relating the voltage across a coil to the flux density in its core is

$$E = 4 \times 10^{-8} f N F_f A_c k_s B_{\max} \tag{1}$$

E = voltage across coil, volts,
f = frequency, cps,
N = number of turns in coil,
F_f = form factor of voltage wave = 1.11 for sine wave,
A_c = over-all cross-sectional area of core = $b \times s$, in.^{2}, (see Fig. 4·1)
k_s = stacking factor for core laminations (see Sec. 4·6),
$B_{\max}$ = maximum flux density in core, lines/in.^{2}.

In this formula the units of linear measure are unimportant so long as the same unit is chosen for A_c and $B_{\max}$; for example, the core area could be given in cm^2 and the maximum flux density in gauss (lines/cm^2).



(a) Shell type (b) Core type

FIG. 4·1.—Iron-core inductor dimensions.

If the voltage and flux are sinusoidal so that $F_f = 1.11$ and if $A_c k_s$ is replaced by its equivalent A_i, the actual cross-sectional area of magnetic material in the core, Eq. (1) becomes

$$E = 4.44 \times 10^{-8} f N A_i B_{\max}. \tag{1a}$$

Coil Dimensions.—In the calculation of inductance, mutual inductance, and interwinding capacitance certain dimensions are involved which are shown in Fig. 4·1 and in the several parts of Fig. 4·2 and tabulated below.

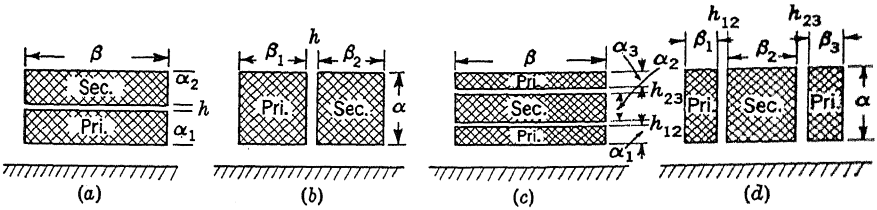


FIG. 4·2.—Coil dimensions.

Symbol	Fig.	Remarks
s	4·1	Stack height depends not only on the number and thickness of laminations in the core, but also on tightness of clamping, etc. (See Sec. 4·6.)
b	4·1	Core width
β, β_1, etc.	4·1, 4·2	Over-all axial length of winding(s) from outside of one end turn to outside of other end turn. This quantity may not be the same for other windings on the same core.
r_m	4·1	Radius of mean turn, measured from corner of stack. Equals mean of radii of inner and outer layers.
α, α_1, etc.	4·1, 4·2	Radial thickness(es) of winding(s), measured from outside of copper of outer layer to inside of copper of inner layer, for each winding.
h_{12}, etc.	4·2	Total thickness of insulation between windings. Measured from surface of copper, not from surface of wire insulation. Axial measurements, as in Figs. 4·2*b* and 4·2*d* are usually of poor accuracy because of difficulty of positioning coil layer ends.

A number of equations might be given to define the relationships between these and other dimensions for particular cases, but since they are all obvious upon inspection of a sketch of the particular coil layout in question they will be omitted.

Leakage Inductance.—For the coil constructions sketched in Figs. 4·2*a* through 4·2*d* the leakage inductances (referred to the primary) are given by the formulas

$$L_{lp} = 1.14 \times 10^{-8} \frac{l_m N_p^2}{l} \left(h_{12} + \frac{\alpha_1 + \alpha_2}{3} \right), \text{ for Fig. 4·2}a, \tag{2a}$$

$$L_{lp} = 1.26 \times 10^{-8} \frac{l_m N_p^2}{l} \left(h_{12} + \frac{\beta_1 + \beta_2}{3} \right), \text{ for Fig. 4·2}b, \tag{2b}$$

$$L_{lp} = 0.283 \times 10^{-8} \frac{l_m N_p^2}{l} \left(h_{12} + h_{23} + \frac{\alpha_1 + \alpha_2 + \alpha_3}{3} \right), \tag{2c}$$

for Fig. 4·2c, and

$$L_{lp} = 0.315 \times 10^{-8} \frac{l_m N_p^2}{l} \left(h_{12} + h_{23} + \frac{\beta_1 + \beta_2 + \beta_3}{3} \right), \tag{2d}$$

for Fig. 4·2d.

In these four formulas

L_{lp} = primary leakage inductance, henry,
l_m = length of mean turn, cm,
N_p = number of turns in primary.

If the coils are not all of the same length, l should be taken as the mean of the several lengths. The h's, α's, and β's have been defined above.

If all linear dimensions are given in inches, the same four formulas apply providing the multiplying factors are all increased by the factor 2.54, giving 2.9, 3.2, 0.72, and 0.8 in Eqs. (2a), (2b), (2c), and (2d), respectively.

Self-inductance.—The calculation of the self-inductance of an iron-core inductor is a laborious procedure because of the nonlinear relationship between the magnetomotive force and the resulting flux and because of the almost invariable presence of an air gap in the core. The calculation of a magnetic circuit of varying cross section and irregular shape is too complicated and too rarely required in the design of transformers to warrant discussion in this chapter. Fortunately for the designer of transformers and reactors, it is usually justifiable to make the following assumptions:

1. The magnetic circuit is of uniform material throughout except for the air gap and is of constant cross-sectional area.
2. The effects of leakage are negligible in that the total flux through all cross sections of the core is the same, and the bypassing of part of the core by the leakage flux can be corrected for by a change in the air-gap effective length.
3. The effect of fringing at the edges of the air gap can be taken into account by a change in the air-gap length.
4. The flux density is constant at all points in the core.

The actual calculation of inductance depends upon the definition of that quantity, which in turn depends upon the particular application of the inductor. For the most purposes the inductance may be assumed to be given by the formula

$$L_s = 1.256 \times 10^{-8} \frac{N^2 A_i \mu_e}{l_i} \tag{3}$$

if the linear dimensions are given in centimeters, or

$$L_s = 3.19 \times 10^{-8} \frac{N^2 A_i \mu_e}{l_i} \tag{3a}$$

if they are in inches. In these formulas,

L_s = self-inductance, henrys,
N = number of turns in coil,
A_i = effective cross-sectional area of core = $b\ s\ k_s$, where b and s are the core width and stack height respectively and k_s is the stacking factor of the core,
l_i = effective length of the magnetic path in the core,
μ_e = effective permeability.

All of the above quantities are definite and easily determinable except for the last two. The actual length of the magnetic path is somewhat ambiguous because of the unknown behavior of the flux at the corners, but is usually assumed to be the center-line length of the core as shown in Fig. 4·1. The value of μ_e is not so easily determined, however.

The permeability of a magnetic circuit is a quantity that is analogous to the electrical conductivity used to calculate the resistance of a piece of wire of known length and cross section. As used here, however, the appropriate value depends upon the properties of the core material, the ratio k_l of the effective air-gap length l_a to the iron-path length l_i, and the conditions of operation. In the case of a power-supply filter choke the value of inductance, which is of interest in predicting the performance of the filter, is what might be miscalled the "d-c" inductance. This inductance is a measure of the energy per cycle that the choke can store up in its magnetic field and depends upon the average value of the coil current. In the case of an interstage transformer, however, this quantity is of little interest, and what is needed is the incremental inductance, which is a measure of the reactance of the transformer primary to the a-c component of the plate current. The case of a line-filter inductor working at very low power levels is different again; here the important quantity is the initial inductance, which determines the reactance of the inductor to small values of alternating current when the core has no initial magnetization. All of these values of inductance will be given by Eq. (3) by choosing the proper value for μ_e.

The effective permeability may be calculated in a number of steps as follows:

1. The effective air-gap length l_a and the length ratio $k_l = l_a/l_i$ are computed.
2. If there is a d-c component present in the coil current and the incremental inductance is required, the operating point on the B-H curve must be determined.

3. The appropriate value of the permeability of core material for the given operating conditions must be determined from the curves for the material.
4. The value of the effective permeability of the whole magnetic circuit must be obtained either graphically or by computation from the permeability found in Step 3.
5. Using the value of the effective permeability from Step 4 and the known dimensions of the core and coil, the inductance may be calculated from Eq. (3).

The calculation of the effective air-gap dimensions is a matter of some difficulty because they depend upon a number of poorly known factors. For long air gaps it is sufficiently accurate to assume that the effective dimensions are the same as the actual dimensions, subject to the corrections discussed below. For lap joints and for close butt joints, however, the effective length is greater than the actual length. A good 100 per cent lap joint will have an effective length of not less than 0.5 mil, and a very good butt joint will have an effective length of at least 3 mils, even if the butting surfaces are ground. It is usually preferable in the case of short gaps to use the length factor discussed below.

Compensation can be made for the effect of fringing in gap lengths less than $\frac{1}{5}$ of either b or s (whichever is the smaller) by assuming that the effective air-gap area

$$A_a = (s + l_a)(b + l_a).$$

Leakage effects can be taken into account by using $2l_a$ instead of l_a in both factors of this product. Within the limitation mentioned this formula will give results accurate to within a few per cent.[1]

In the interest of simplifying the inductance formula it is useful to calculate a fictitious air-gap length—the length of a gap of area equal to A_i which would have the same reluctance as the actual air gap—and then to calculate the length ratio k_l of iron path to effective air path. This effective gap length will then be

[1] Excellent discussions of the calculation of fringing and leakage fluxes are to be found in the following: H. C. Roters, *Electromagnetic Devices*, Wiley, New York, 1941, Chap. V and in MIT Electrical Engineering Staff, *Magnetic Circuits and Transformers*, Wiley, New York, 1943, pp. 68–93.

A discussion of the design of iron-core inductors for optimum Q will be found in four articles from the *Gen. Radio Experimenter:* L. B. Arguimbau, "Losses in Audio-frequency Coils," November, 1936; P. K. McElroy and R. F. Field, "How Good is an Iron-cored Coil?" March 1942. P. K. McElroy, "Those Iron-cored Coils Again," December 1946 and January 1947. These four articles are available in reprint form from the General Radio Co., 275 Massachusetts Ave., Cambridge 39, Mass.

$$l_{ae} = l_a \frac{bsk_s}{(b + 2l_a)(s + 2l_a)} \tag{3b}$$

and the length ratio $k_l = l_{ae}/l_i$.

Since l_a is unknown or inaccurately known except for long gaps it is better for lap-joint and close-butt-joint cores to assume a value for k_l according to the following rules.

The factor $k_l = 0$ only for continuous ring cores, which are seldom of interest for transformers or reactors. For lap joints a value of 5×10^{-5} can be attained with great difficulty in the largest core designs; in small cores 10^{-4} can be attained with great difficulty, with 2×10^{-4} within the best practical range, and 3×10^{-4} well within ordinary practice. For close butt joints a reasonable assumption would be 2 to 10 mils for the effective length; if accurate inductance values are necessary the inductors must be adjusted by shimming the air gap.

If b is the width of the core laminations and s is the over-all height of the lamination stack, the effective core area $A_i = bsk_s$. The stacking factor k_s depends on the thickness of the laminations and of the oxide or other nonmagnetic coating upon the lamination surfaces, on the tightness of clamping of the stack, on the choice of a butt or a lap joint, and on various mechanical factors such as lamination flatness, freedom from burrs, etc. The stacking factor varies from about 0.95 for medium-gauge laminations in a butt-jointed core to as low as 0.4 for very thin laminations such as are sometimes used for r-f transformers. For 29-gauge (0.014-in.) laminations the Allegheny-Ludlum Steel Company uses a factor of 0.94 for butt-jointed and 0.88 for 100 per cent interleaved stacks. The stacking factor may be determined for a particular stack by weighing and dividing the apparent density of the stack by the density of the material. For the purposes of the Epstein Test it is standard practice to assume a density of 7.7 g/cm³ (0.278 lb/in.³) for silicon steel of a silicon content of less than 2 per cent and 7.5 g/cm³ (0.271 lb/in.³) for higher silicon contents. The actual density, however, varies with both composition and metallurgical treatment, and for accurate calculations the correct value should be obtained from the manufacturer.

Having established the "effective" dimensions of the magnetic circuit the coordinates of the operating point on the B-H curve must be determined. This determination may be omitted if there is no d-c component in the coil current, but unfortunately this is seldom the case for any inductor for which the self-inductance is of importance. The values of the flux density B_o and the magnetizing field strength H_o at the operating point are most easily determined by a graphical method illustrated in Fig. 4·3. Two quantities, B_1 and H_1, are calculated from the equations

$$H_1 = 1.256 \frac{NI_{\text{d-c}}}{l_i}, \qquad \text{oersteds,} \tag{3c}$$

and

$$B_1 = \frac{H_1}{k_l}, \qquad \text{gauss,} \tag{3d}$$

where

N = number of turns in coil,
$I_{\text{d-c}}$ = d-c component of coil current in amperes,
l_i = length of iron path in cm,
k_l = air-gap length factor = l_{ae}/l_i.

(If inch dimensions are used the constant becomes 3.19 instead of 1.256 and H_1 will be in gilberts per inch and B_1 in maxwells per square inch.)

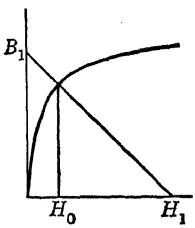


FIG. 4·3.—Graphical determination of operating point.

On a plot of the B-H curve for the material (the plot must be made with *linear* scales for both B and H) a straight line is drawn connecting the points $(0, B_1)$ on the B-axis and $(H_1,0)$ on the H-axis. The intersection of this line with the B-H curve of the core material is the operating point, and the coordinates B_o and H_o of this point are the values used in determining the effective permeability.

If the initial inductance or the d-c inductance are the desired quantities the previous step may be omitted and the permeability of the core will be μ_i, the initial permeability, or $\mu_o = B_o/H_o$, the "d-c" permeability. If the incremental inductance is desired the incremental permeability $\mu_{\text{a-c}}$ must be obtained from curves furnished by the core-material manufacturer, such as those of Fig. 4·4. The value of H_o is obtained graphically as just described; that of $B_{\max}$ is calculated from Eq. (1). The latter value need not be computed with great accuracy since $\mu_{\text{a-c}}$ changes slowly with changes in $B_{\max}$.

The effective permeability μ_e of the magnetic circuit as a whole is obtained from the appropriate value of core-material permeability and the curves of Fig. 4·5; or it may be computed from the formula

$$\mu_e = \frac{\mu}{1 + \mu k_l} \tag{3e}$$

where μ_e is the quantity required for the calculation of inductance from Eq. (3), k_l is the air-gap length ratio, and μ is the appropriate core-material permeability. The computation of L_s from Eq. (3) completes the inductance calculation.

In actual practice inductance calculations are not as involved as might be inferred from the description just given. The lamination

catalogues usually give data for each stock lamination which greatly facilitate the calculations, especially for cores with no air gap. If there is no d-c component in the coil current, Step 2 above may be omitted, since in this case $H_0 = 0$. The calculations of effective air-gap dimensions need not be made with great accuracy in most cases since the actual dimensions are not accurately known; for lap joints it is usually

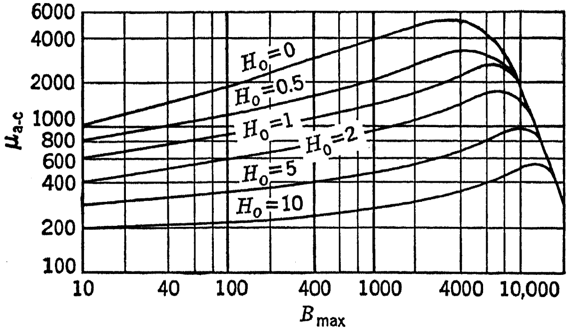


FIG. 4·4.—Incremental permeability curves for Allegheny Audio Transformer "A" sheet steel.

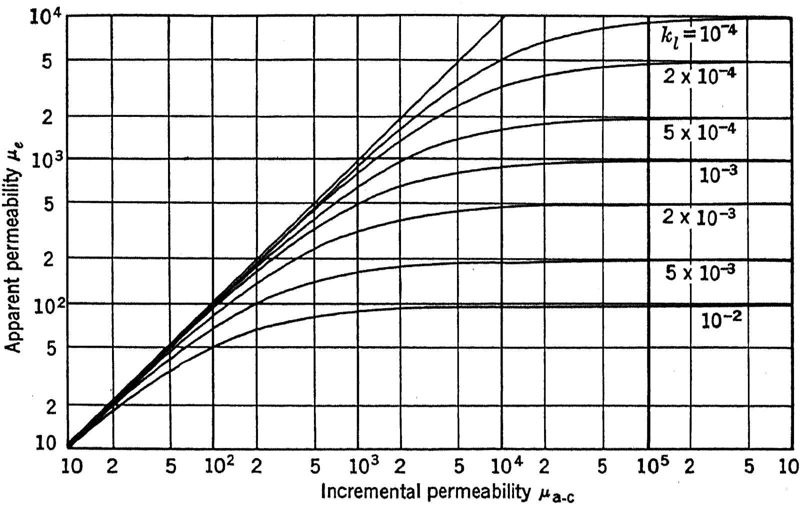


FIG. 4·5.—Effective permeability of core with air gap.

safe to assume a value for k_l from the rules given above. Finally it should be remarked that an attempt to calculate the inductance of an iron-core coil with high accuracy is futile because the inductance itself is affected by so many variable factors. The same remark applies to almost all other coil calculations. All of the above equations assume the use of the centimeter as the unit of length; if the inch is used instead

the same equations apply if the factor 1.256 is replaced by 3.19 in Eqs. (3), (3*b*), and (3*c*).

Winding Capacitance.—Calculations of the interwinding and distributed capacitances of layer-wound coils are inherently of low accuracy because of inaccurate knowledge both of the dimensions involved and of the effective dielectric constant of the heterogeneous mixture of insulating materials used in the construction of the coil. They are principally of use in making rough estimates of the performance of transformers at high frequencies and in determining the effects of proposed modifications in the construction of a particular coil.

The distributed capacitance of a multilayer coil is given approximately by the expression

$$C_d = \frac{0.12\epsilon l_m \beta (n_l - 1)}{d n_l^2}, \tag{4a}$$

where

C_d = distributed capacitance of coil, $\mu\mu$f,
l_m = length of mean turn of winding, cm,
β = axial length of winding, cm,
ϵ = effective dielectric constant of insulation,
n_l = number of layers of wire,
d = distance between copper of one layer and copper of next layer, cm.

This formula neglects the effect of fringing at the ends of the layers and the capacitance between turns in each layer, but both of these effects are small in most windings and the formula is too inaccurate in practice to make it worth while to include corrections. The interlayer distance d depends both on the actual thicknesses of the wire insulation and interlayer paper and upon the adjustment of the winding machine; if the wire is springy or if it has a rough surface, as is the case with fibrous insulations, and if it is not wound with sufficient tension, there will be some springing apart of the layers, and a resultant decrease in capacitance. The average dielectric constant varies in practice from about 2 for unimpregnated coils to about 3 for the conventional paper-insulated and wax-impregnated coils.

The capacitance between two adjacent windings of a coil is given by the expression.

$$C_i = 0.12\epsilon \frac{A_m}{d_i} \tag{4b}$$

where

C_i = interwinding capacitance, $\mu\mu$f,
d_i = copper-to-copper distance between windings, cm,
A_m = mean area of adjacent surfaces of windings, cm^2.

If the linear dimensions used in the above equations are given in

inches instead of centimeters the constants should be increased from 0.12 to 0.30.[1]

Resistance.—The d-c resistance of a coil is given with fair accuracy by the expression

$$R = Kl_m N\rho, \tag{5}$$

where

R = resistance, ohms,
l_m = length of mean turn, cm,
ρ = resistivity of wire, ohms per unit length,
N = total number of turns in coil,

and the constant K depends upon the units used. In the United States it is customary to give ρ in ohms per thousand feet; if l_m is given in inches, K becomes 1/12,000. This formula is theoretically accurate; in practice the accuracy is limited by variability of the wire (which is seldom more than a few per cent) and inaccuracy in the calculation of l_m, which is given by

$$l_m = 2s + 2b + 2\pi r_m, \tag{5a}$$

where r_m is the radius from the corner of the core to the mean turn. This radius is greater than the sum of all the layers of wire and insulation thicknesses involved by an amount that depends upon the so-called "build factor" k_b. This factor is analogous to the stacking factor of the core, and depends upon the springing of the wire in winding. It varies from about 0.75 for a coil with many layers of very light or very heavy wire, or with numerous secondaries, to about 0.95 for a compact single winding of medium-gauge wire. It also depends upon the type of winding machine used, and ability of the machine operator, and the general shop practice of the winding department. A build factor of 0.85 is safe for design purposes except in extreme cases. The value of r_m may be taken as the sum of the thicknesses of all the layers of wire and insulation between the mean turn and the core, divided by the build factor.

An alternative method of calculating l_m is to assume that $k_b = 1$ and to use the factor 3.22 instead of π in Eq. (5a). This amounts to assuming that $k_b = 0.977$, but it has worked well in practice for one manufacturer.

Temperature Rise.—Because of the inherent complexity of the phenomena involved, thermal calculations for transformers are cap-

[1] If Eqs. (4a) and (4b) are derived from standard capacitance formulas such as Eqs. (122) and (122a) in Terman's *Radio Engineers' Handbook*, p. 112, the constants come out 0.2244 and 0.08842 for the inch and centimeter cases. It is not obvious why they should be different for coil capacitance, though it may be due to false assumptions as to coil dielectric constant, but capacitances given by Eq. (4a) or (4b) can be used in practice to calculate resonant frequencies within a few per cent of measured values in most cases. Neither these formulas nor Terman's Eq. (114) (*ibid.*, p. 101) are accurate for windings with a very small number of layers.

able of giving only order-of-magnitude estimates of temperature rise. The two following equations are usually employed in the design of small transformers.

The temperature rise of the core is given by the expression

$$\Delta T_i = 116 w_i \frac{M_i}{A_{id}}, \tag{6a}$$

where

ΔT_i = rise in temperature of the core, °C,
w_i = core loss, watt/lb,
M_i = weight of core, lb,
A_{id} = exposed area of core available for dissipation, in.^{2}

The temperature rise of the coil is given by the formula

$$\Delta T_c = 160 \frac{W_c}{A_{cd}}, \tag{6b}$$

where

ΔT_c = rise in temperature of the coil, °C,
W_c = total copper loss, watt,
A_{cd} = exposed area of coil available for dissipation, in.^{2}

These formulas are based on several doubtful assumptions: that there is no heat flow between coil and core; that the dissipation factors of the two are 0.00863 watts/in^2 per °C for iron and 0.00625 watts/in^2 per °C for the coil surface; and that the unit is uncased and all heat is removed by forced-air circulation or by conduction from the exposed surfaces. The formulas are useful principally as a check to ensure against unreasonably great temperature rises, and as aids in making the initial choice of core.

4·2. Reactors.—Compared with other types of iron-core inductors the design of a reactor is usually fairly simple, and several short-cut methods are available. The simplest case is that of a reactor with no direct current in the windings, for which $H_0 = 0$ and the laborious graphical computation of the effective value of $\mu_{a\text{-}c}$ can be avoided. If in addition the air gap is of negligible length, $\mu_e = \mu_{a\text{-}c}$, and another step is saved in the inductance calculation as outlined in Sec. 4·1, but this is seldom the case. For most magnetic core materials the permeability is high enough so that even the smallest attainable air gap appreciably increases the reluctance of the core, and in most cases the nonlinearity of the core material introduces objectionable distortion in the current or voltage wave. This distortion can be greatly reduced by providing a series air gap, in the same way that a high-resistance multiplier makes the scale of a rectifier-type voltmeter accurately linear. For a particular core and coil a curve of inductance vs. air-gap length can easily be plotted for a given impressed voltage by using the curves of Fig. 4·5.

This curve will be approximately correct for other values of voltage since except near saturation $\mu_{a\text{-}c}$ changes slowly with B_{max} and the air gap helps to decrease the effect of such changes as do occur.

The calculation of d-c reactor inductance is more laborious since a different value of H_0 must be determined for each new value of k_l or $I_{d\text{-}c}$. There is a short-cut method that is useful if a number of reactors are to be designed using the same core material. This method[1] involves the preparation of a master curve of $LI^2_{d\text{-}c}/V_i$, vs. $NI_{d\text{-}c}/l_i$. The master curve is the envelope of a family of individual curves each of which applies to a particular value of air-gap length. These individual curves may be prepared by the method of Fig. 4·3, but a much less laborious method involves the preparation of a set of "sheared" curves[2] of flux vs. magnetomotive force, as shown in Fig. 4·6. From each of these sheared curves a secondary curve is prepared using the identity

$$\frac{LI^2_{d\text{-}c}}{V_i} = \frac{NI_{d\text{-}c}}{l_iA_i} \tag{7}$$

and plotting against $NI_{d\text{-}c}/l_i$. The envelope of the secondary curves thus obtained is the desired master curve. Such a master curve is shown in Fig. 4·7.

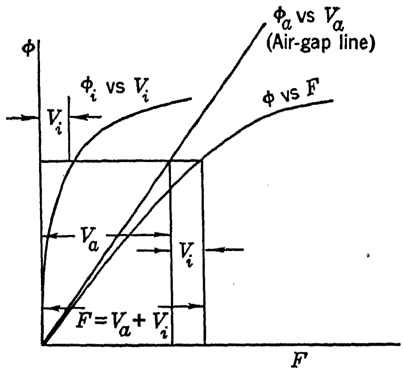


FIG. 4·6.—Sheared-curve construction. F = total magnetizing force. ϕ = total flux. V_a = magnetic potential drop in air gap. V_i = magnetic potential drop in iron.

The design of a reactor by the use of this master curve then becomes a fairly simple matter; a core is chosen and a coil that will fit in the window is designed using the size of wire required for the rated value of $I_{d\text{-}c}$. This design fixes the value of N; $NI_{d\text{-}c}/l_i$ is computed and the value of $LI^2_{d\text{-}c}/V_i$ is determined from the curve. The value of L is known and thus the stack height needed to give the required core volume may be computed. If this stack height is reasonable the design is complete. The value of the air gap may be obtained from a curve similar to that of Fig. 4·8, which may be prepared from data obtained in the calculations that were used in preparing the previous curve. The curve of Fig. 4·8 was actually obtained by measurements of the optimum gap length vs. magnetizing force on about one hundred chokes, and is accurate within

[1] C. R. Hanna, "Design of Reactors and Transformers Which Carry Direct Current," *Trans. A.I.E.E.*, **46**, 155 (1927). Outlined in F. E. Terman, "Radio Engineers' Handbook," pp. 103–4.

[2] M.I.T. Electrical Engineering Staff, "Magnetic Circuits and Transformers, Wiley, New York, 1943, p. 73.

a few per cent. A final check on the design may be secured from the curves of Fig. 4·9, which gives curves of filter-choke inductance vs. weight for various d-c current ratings.

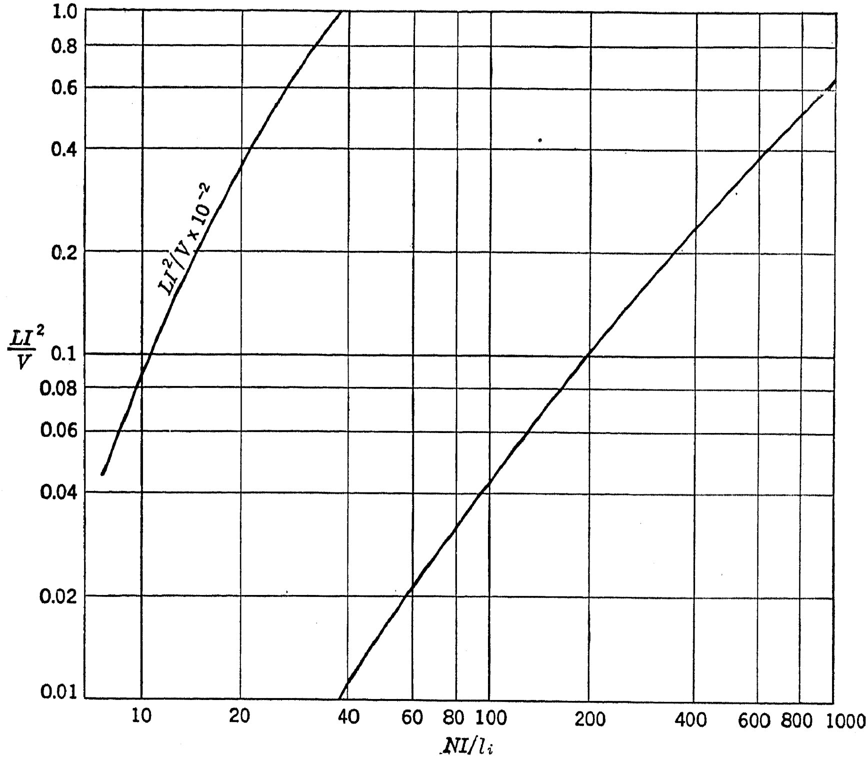


FIG. 4·7.—Master curve of $LI^2_{d\text{-}c}/V_i$ vs. $NI_{d\text{-}c}/l_i$ for Audio Transformer "A" sheet steel.

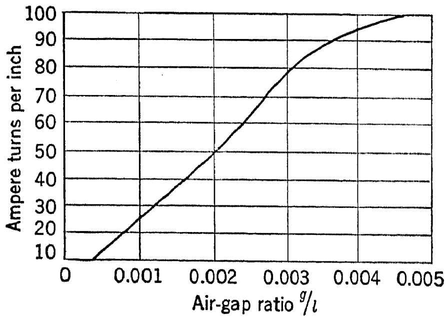


FIG. 4·8.—Filter-choke optimum air-gap ratio for Audio Transformer "A" sheet steel. (Air-gap ratio g/l is the same as k_l in the text.)

The short-cut method just outlined gives results that are fairly accurate only for small values of a-c voltage across the coil, therefore it can be used only for such applications as second or third chokes in

choke-input filters, etc. In power-supply filters the actual value of inductance used makes little difference in performance in most cases, so long as the inductance is above a certain minimum. For this reason chokes designed by the short-cut method may usually be used without regard to the a-c voltage, especially since the value of $\mu_{a\text{-}c}$ increases with increasing B_{max} until saturation is approached. Even operation beyond the knee of the saturation curve has its merits; the decrease of inductance with current peaks gives better voltage regulation to the power supply.

A more accurate but more laborious method must be used for the design of reactors such as modulation chokes and plate-circuit audio

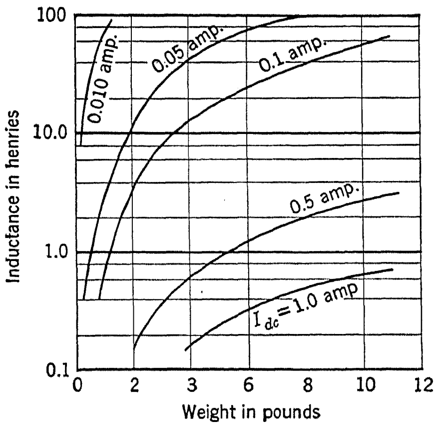


FIG. 4·9.—Filter-choke inductance as a function of weight.

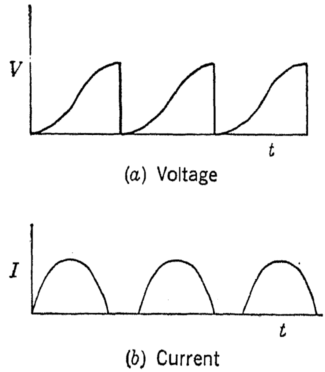


FIG. 4·10.—Voltage and current waveforms in resonant-charging choke.

reactors, for which the a-c component of coil current cannot be neglected with regard to the d-c component. For such reactors the complete inductance calculation outlined in Sec. 4·1 must be used; a core, coil, and air gap are chosen on the basis of previous experience and the inductance is calculated for the given operating conditions. The design is modified by successive approximations until the calculated inductance is within the specified range. No general method of procedure can be given since the requirements vary too widely in various cases.

This general method is used in the design of the resonant-charging chokes used in line-type radar modulators, but with a variation developed at the Radiation Laboratory. The voltage and current curves in such chokes are far from sinusoidal; typical waveforms are shown in Fig. 4·10. The values of the peak and the average currents are known from circuit considerations; B_{max} is obtained from the B-H curve and the value of the *peak* current and is used for the value of B_1 in drawing the reversed air-gap line of Fig. 4·3; H_1 is calculated from the *average*

value of the current. From this point on the design method is the same as outlined in Sec. 4·1.

4·3. Power Transformers.—The exact sequence of operations in the design of a power transformer depends both upon the purpose of the transformer and upon the habits of the individual designer. The following data are ordinarily furnished:

Supply voltage,
Supply frequency,
Number of outputs required,
Voltage of each output,
Current of each output.

In addition any or all of the following may be specified:

Waveform of supply voltage (if not approximately sinusoidal),
Power factor of load(s),
Presence of direct current in any of the windings, and its value,
Permissible temperature rise,
Permissible voltage regulation,
Size and weight limitations,
Other special requirements.

From the given data certain quantities may be calculated at once. The output voltage and current for each winding are multiplied to give the output volt-amperes for each, and unless one or more of the loads is specified to have a power factor different from unity the sum of the output volt-amperes is assumed to be the total power output. Because the ordinary small power transformer has a full-load efficiency of about 90 per cent the sum of the output volt-amperes is multiplied by 1.1 (usually) and the product taken as the input power. This figure is again multiplied by 1.1 since the input power factor is also about 90 per cent in most cases, and the resulting input volt-amperes are divided by the supply voltage to obtain the input current.

After the currents for all the windings are obtained, the wire sizes for each can be chosen to give appropriate current densities. Table 4·4 of Sec. 4·6 gives values of circular mils per ampere that will result in approximately a 40°C temperature rise in transformers of the ordinary construction when operated at 60 and at 400 cps. If some other temperature rise is desired the current density may be changed accordingly, since the rise will be approximately proportional to current density, or inversely proportional to the number of circular mils per ampere.

After the wire sizes for each winding are obtained the interwinding and interlayer insulations can be chosen, but the coil layout cannot be completed until the actual number of turns in each coil and the core

window size are known. There are many different ways of choosing a core for a trial design; one designer may work to a standard flux density, another to a particular figure of core loss, another to a given value of watts output per pound of core, etc., but all such rules lead to about the same place in the end. Since temperature rise was the chief limitation for most of the transformers designed at the Radiation Laboratory, Eq. (6*a*) was usually taken as the starting point. A core was chosen whose weight and exposed area were such as to give the permissible temperature rise with a reasonable value of core loss, and this value was used to obtain the working value of B_{max} from the core-loss curves for the core material used.

After obtaining the value for B_{max} the number of turns on the primary can be computed from Eq. (1), using the input voltage for E, and from the number of primary turns the numbers of turns for each of the other windings can be calculated by the use of the appropriate voltage ratios. Choosing the core also establishes the window size, and a preliminary coil layout is made The winding tables used at the Radiation Laboratory are reproduced in Sec. 4·6, and contain sufficient information for the design of any ordinary coil up to a capacity of 1 kw or more.

The preliminary coil layout can be checked against the window size. If it will not go into the space a larger core must be chosen; if it does not nearly fill the window a smaller one should be used, and in either case the calculations must be repeated starting with the new value of B_{max}. Some labor may be saved if the coil is not too far from the correct size by using the same lamination size and changing the stack height. In commerical transformer design the stack height is usually changed in steps to correspond with the sizes of stock core tubes. If the tentative design is not far from the desired goal the resulting stack height will have a reasonable value and the design will be complete; if the necessary stack height is unreasonably large or small a new lamination size must be chosen and the calculations repeated.

Weight vs. Temperature Rise.—In most design, especially for airborne equipment, the designer is always under pressure to decrease the size and weight of his components to a minimum. The most important obstacle to the attainment of this goal is the rise in temperature of the unit, and this is especially true of power transformers. It might appear that an increase of the efficiency of a transformer from say 90 to 95 per cent would be of little benefit, but such an increase would decrease the losses by one half and would therefore decrease the temperature rise in the same ratio (assuming conductive or still-air cooling). A decrease in the temperature rise would permit the over-all size to be decreased if the same ambient and maximum temperature limits held.

The relationships between power output, weight, and temperature

rise are shown for certain typical small power transformers by the curves of Figs. 4·11 and 4·12. It can be seen that much weight can be saved by allowing a greater temperature rise. Since the ambient temperature is usually fixed by conditions beyond the control of the transformer designer the only way in which a greater temperature rise can be obtained is to raise the operating temperature limit. There are several ways of doing this; the losses may be decreased by better materials and improved design, insulating materials may be used which have satisfactory life at

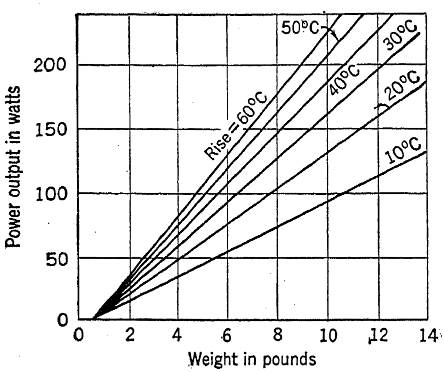


FIG. 4·11.—Power output vs. weight.

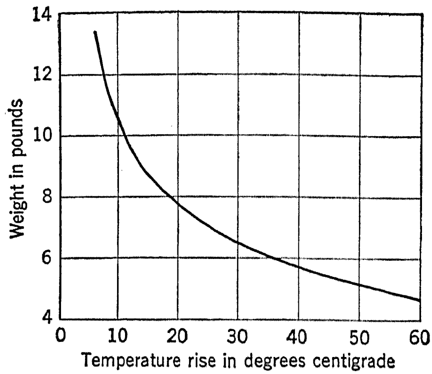


FIG. 4·12.—Weight vs. temperature rise for 100-watt 60-cps transformer.

a higher operating temperature, or conventional transformers may be operated at excessive temperatures with resulting decreased life. A typical curve of life vs. operating temperature is shown in Fig. 4·13. Tests on one group of transformers showed that an average life of 200 to 300 hr could be consistently obtained at operating temperatures of 150° to 160°C.

A second method of raising the permissible operating temperature involves the use of the new high-temperature insulations such as Formvar and Fiberglas wire insulations, silicone-varnished Fiberglas cloth interlayer insulation and wrappers, and silicone impregnants. Tests indicated that transformers using these materials would have satisfactory operating lives at temperatures of 190° to 200°C, but not enough work was done at the Laboratory to establish accurate life curves. These temperatures, incidentally, are far above the rated maximum for Formvar.

High-frequency Operation.—Another effective method of reducing the size and weight of a transformer is to operate at a higher frequency. At 60 cps with conventional shell-type cores it is not usually possible to work the core to its full rating since the excitation limit will be passed before the maximum permissible core loss is reached. In other words, if a core loss of 4 watts/lb were permitted by the allowable core temperature

rise, it would probably be found that the excitation current would become as large as the load current at flux densities corresponding to a core loss of 2 watts/lb or less. At 60 cps, therefore, the flux density is limited primarily by the copper losses; at 400 cps the limit is usually the iron losses.

For a given transformer the maximum output power is determined by the maximum allowable primary voltage and current. The voltage is ultimately a function of the flux density in the core and the current a function of the current density in the winding. If a given coil is assumed and its size and current density held constant then for constant power

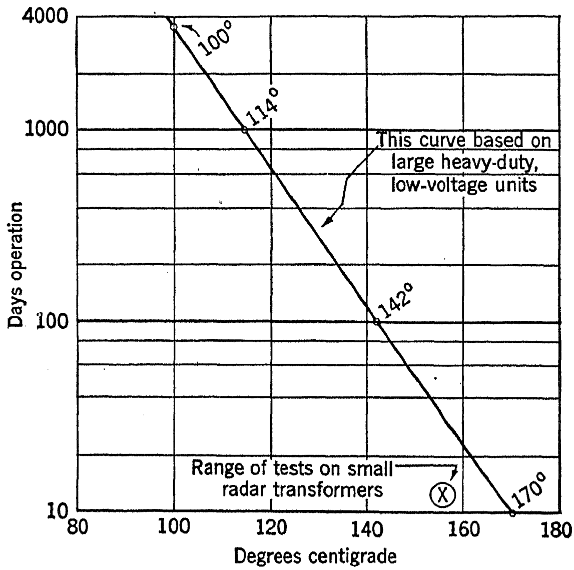


FIG. 4·13.—Transformer life vs. operating temperature.

output the input voltage must be held constant. Under such conditions the formula $E = 4.44NfBA \times 10^{-8}$ reduces to $A = K/(fB,)$ where A is the cross-sectional area of the core, f is the frequency, and B is the flux density. Since the core weight is directly proportional to A it follows that it is inversely proportional to the product of f and B. The weight saving on going from 60 to 400 cps is about 3.5 to 1 for the core, but since little weight can be saved on the coil and housing the actual saving for the complete transformer is only about 2.5 to 1. For core materials of ordinary quality the additional saving on going from 400 to 800 cps is about 20 per cent for the core or 10 per cent for the complete unit. With high-quality materials it would be possible to save 25 per cent by the use of 800 cps. Above 800 cps the weight remains fairly constant, and above 2400 cps it increases slightly.

Three-phase Operation.—For high-power applications it is preferable to use 3-phase rather than single-phase supply. The difference in weight between a single-phase and a 3-phase transformer is small, but the overall weight of a d-c power supply is much less when operated with a 3-phase transformer because a much lighter filter can be used. An appreciable weight saving can also be made for the case and potting compound of a 3-phase transformer. Figure 4·14 shows such a unit with the cover of the case removed, and demonstrates the efficient utilization of the space within the case by the 3-phase transformer.

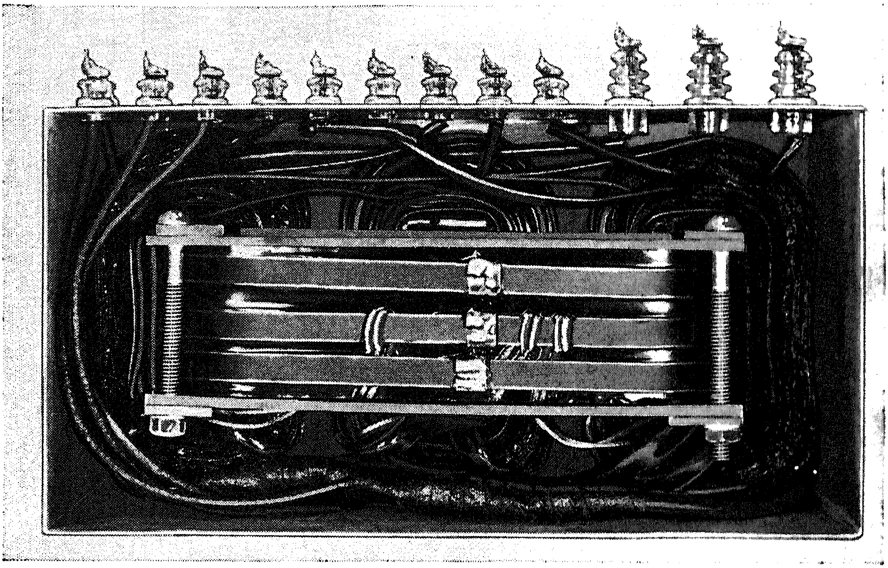


FIG. 4·14.—Three-phase transformer in case.

An idea of the weight savings permitted by 3-phase operation can be obtained from Table 4·1, which gives the weights of single-phase and 3-phase power supplies for three typical cases. It is not ordinarily advisable to use 3-phase power below about 750 watts, and even up to 1200 watts single-phase is usually preferable.

TABLE 4·1.—WEIGHTS OF SINGLE- AND 3-PHASE POWER SUPPLIES

D-c output	Weight, lb single-phase	Weight, lb 3-phase
1.25 amp at 400 v, 0.5% ripple	27	21.5
0.2 amp at 8000 v, 0.015% ripple	149	46.5
0.21 amp at 400 v, 0.02% ripple, 0.5 amp at 850 v, 0.02% ripple, and 1.2 amp at 1600 v, 0.04% ripple	168.5	77.5

Weight Reduction by Improved Design.—Almost all small power transformers used in electronic equipment adhere to a single conventional type of construction using shell-type cores, usually made up of E-I laminations stacked either 1 by 1 or in groups of 5 to 10, and with all windings in a single coil structure. Although such transformers are satisfactory for most purposes and are comparatively inexpensive to manufacture, they can be considerably improved by careful design. One example of such an improvement was given by Harrison.[1] He used a core-type construction with two symmetrical coil assemblies as shown

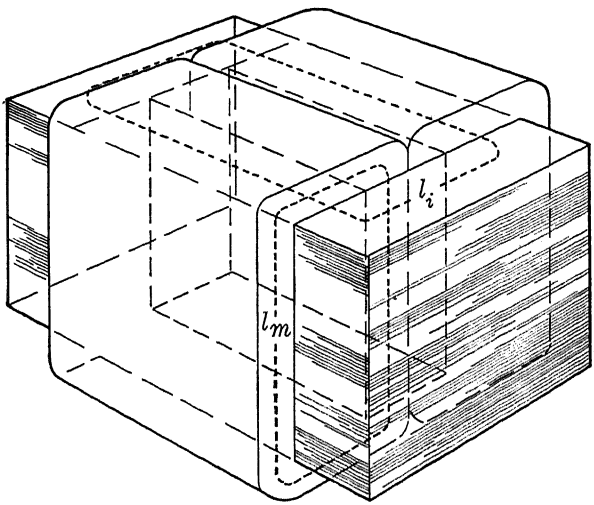


FIG. 4·15.—Core-type transformer with balanced coils.

in Fig. 4·15, and designed his transformer according to the following rules that lead to the maximum efficiency:

1. The total core loss should equal the total copper loss at full load.
2. The mean length of the magnetic circuit should equal the mean length of the copper circuit.
3. The over-all cross-sectional area of the core should equal the area of the core window.

These rules are based on certain assumptions as to stacking and space factors, etc., which are fairly well justified in practice. The coils resulting from the use of such a core as that shown in Fig. 4·15 are long solenoids with their magnetic axes closely spaced, giving an almost perfect astatic construction if the several windings are split with half of each

[1] E. B. Harrison, "High-Quality Communication and Power Transformers, *Jour. Soc. Motion Picture Engrs.*, 43 No. 3 pp. 155–167 (Sept. 1944).

winding placed on each core leg. This astatic or "humbucking" construction results in a great reduction of the stray field of the transformer, which is important when it is to be placed near other transformers operated in low-level circuits. The small radial thickness of the coils permits heat developed in the winding to flow out to the surface of the coil though the minimum thickness of low-heat-conductivity material, and the large exposed surface of the coils aid in securing efficient cooling, whereas the shape of the whole assembly affords maximum utilization of the space within a rectangular can. The proximity of the large end surfaces of the core to the walls of the case also aids in efficient cooling.

Several somewhat unusual precautions were taken in the assembly of these units, and resulted in improved performance and reduced losses. The interleaved cores of the power transformers did not require core bolts, but in the case of filter reactors of the same construction, which had air gaps to prevent d-c saturation, the cores were clamped together by means of flanged clips over the core ends and held together by long bolts outside the core and coil structure. The removal of high-loss steel clamping devices from the field of the unit resulted in a considerable increase in the Q of the reactor: audio reactors of this construction have shown a Q of 70 at 1000 cps. In interleaving the laminations of the transformer cores it was found that as much as a 50 per cent increase in incremental permeability could be secured at high flux densities by stacking the laminations two by two instead of one by one. These two constructions are shown in Fig. 4·16, which indicates schematically the flux paths in the two cases. The two by two stacking results in a somewhat longer effective air gap, but the increase in air-gap reluctance is more than compensated for by the reduction of high-flux-density areas and a consequent increase in the permeability of the total core structure.

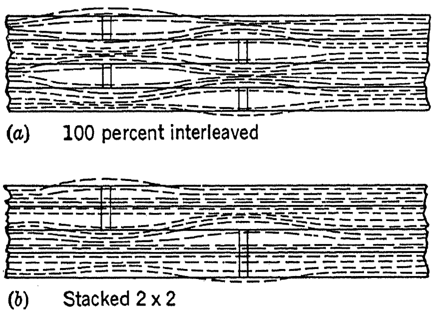


FIG. 4·16.—Flux paths at lamination lap joints.

Table 4·2 gives data showing the improvement in characteristics which is obtained in going from a high-quality power transformer of the conventional type to one of the new construction. Both transformers used the same materials and techniques, and the improvement shown is due entirely to the improved design. The cases were of the same height, so that the volumes of the units were also in the ratio of 47 to 23, or nearly 2 to 1. These transformers were designed for use in high-quality audio equipment, and no particular effort was made to reduce the weight.

In view of the small losses it is probable that they could be considerably reduced in size without exceeding a safe operating temperature.

TABLE 4·2.—COMPARISON OF SHELL- AND CORE-TYPE TRANSFORMERS

	Conventional shell-type	Improved core-type
Rating, va	360	350
Efficiency, %	92.7	96
Total losses, watts	27.7	15
Weight, lb	$29\frac{1}{4}$	$17\frac{1}{2}$
Chassis space required, in²	47	23

Another example of weight and size reduction by judicious redesign and the use of new materials and techniques is afforded by a series of CRT high-voltage power supplies designed and built at the Radiation Labora-

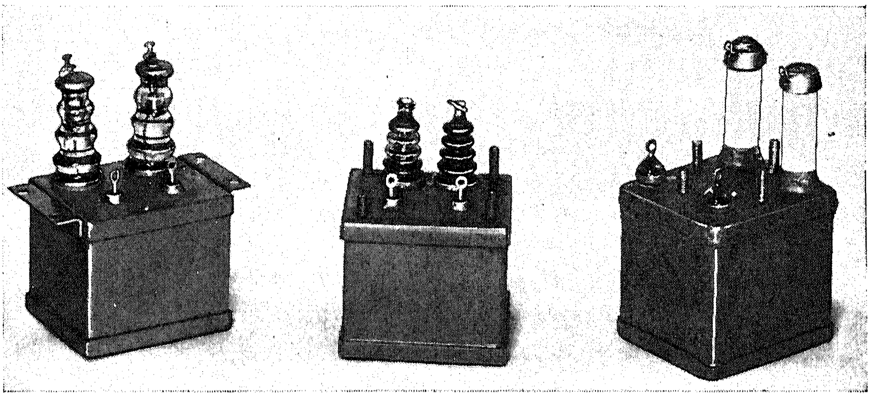


FIG. 4·17.—High-voltage transformers.

tory. These units, which were intended for airborne operation at 400 to 800 cps, used high-voltage selenium-rectifier stacks in a full-wave voltage-doubler circuit, thereby eliminating the filament-power requirements of tube rectifiers, halving the voltage needed from the high-voltage transformer, and minimizing the required filter-condenser capacitance. Three of the high-voltage transformers, designed for d-c output voltages from 4 to 10 kv, are shown in Fig. 4·17. Although the rms secondary current was only 6 ma, the use of No. 40 wire for mechanical reasons provided a copper area of over 1600 circular mils per ampere, or about twice the minimum usually specified. The kraft paper interlayer insulation was worked at a voltage gradient of not over 100 volts per mil. Single or double RL No. 11 or 12 Hypersil cores were used at maximum flux densities of from 64 to 77 kilolines/in.², which gave core losses of from 4 to 6 watts/lb.

The transformers were housed in hermetically sealed steel cases fitted with solder-seal glass or porcelain bushings and filled with sand and oil. No expansion bellows were used, but the flat sides of the cases were sufficiently flexible so that no leakage or expansion troubles were observed up to temperatures of 105°C. The transformers shown in Fig. 4·17 have outside case dimensions of 2 to $2\frac{1}{2}$ in. and weigh about 1 lb; a typical 4-kv transformer of conventional design measures about 3 by 4 by 5 in. and weighs $4\frac{1}{4}$ lb. These transformers and power supplies were satisfactory in service and had few failures.

Still another example of weight-saving in transformer design is afforded by a unit which was designed for CRT high-voltage supply and

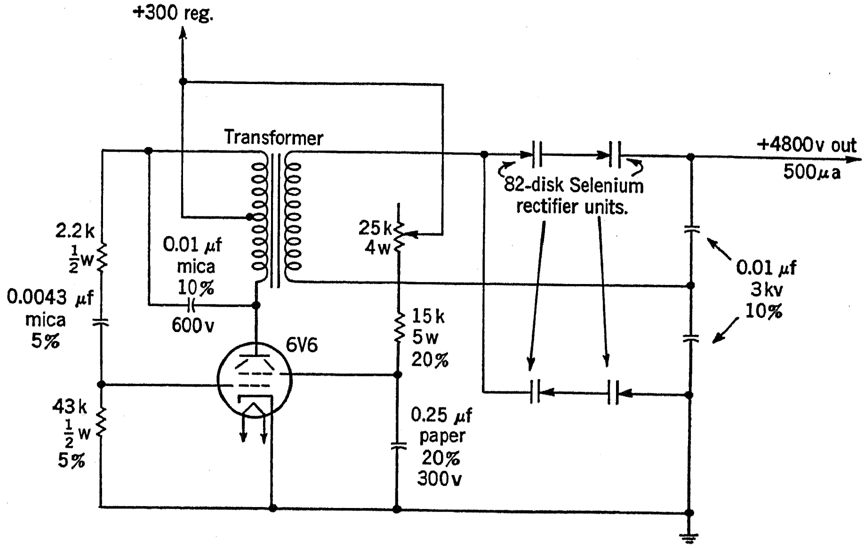


FIG. 4·18.—A-f oscillator power supply.

operated at a frequency of about 3000 cps. The primary of the transformer served as the tank coil of a 6V6 Hartley oscillator, the complete circuit being given in Fig. 4·18; the construction of the unit is shown by Fig. 4·19. Since it was intended for airborne operation it was essential to enclose as much of the high-voltage portion of the circuit as possible in a hermetically sealed container, and therefore the transformer, the four selenium-rectifier units, and the two output condensers were placed in a single oil-filled can. Only four bushings were required, three low-voltage ones for the input connections and a high-voltage one for the d-c output. A metal bellows on the outside of the can took care of the expansion of the rather large volume of oil.

The operating frequency of such a unit is not critical, the upper limit being fixed at approximately 10 kc/sec by the increase of core loss

at high frequencies and by the effects of distributed capacitance. The lower limit is fixed by the increasing size and weight of the unit necessary for low-frequency operation.

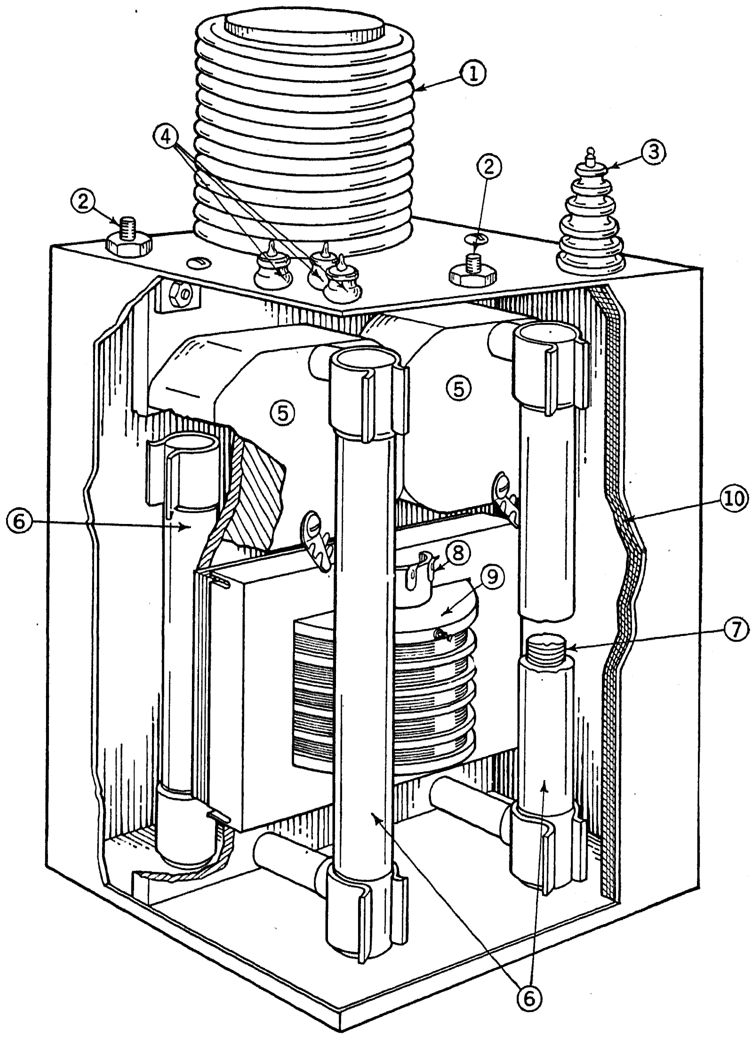


FIG. 4·19.—Transformer-rectifier unit; (1) expansion bellows; (2) mounting studs; (3) high-voltage d-c output bushing; (4) input bushings; (5) mica condensers; (6) high-voltage selenium rectifier stacks; (7) rectifier disks; (8) exposed end of primary coil form; (9) grooved secondary coil form; (10) internal bakelite can insulation.

The design of the transformer starts with a choice of the operating frequency and the full-load Q of the oscillator plate-tank circuit. A compromise between efficiency and regulation must be made in choosing the value of Q; the optimum value depends upon the driver tube, but for

a given tube an increase in Q improves the regulation but decreases the efficiency. Values from 3 to 10 are satisfactory for a 6V6 driver operated at a plate voltage of 300. The primary inductance necessary is given by $L = R/2\pi fQ$, where R is the equivalent total parallel tank-circuit resistance. A second compromise is necessary between allowable trans-

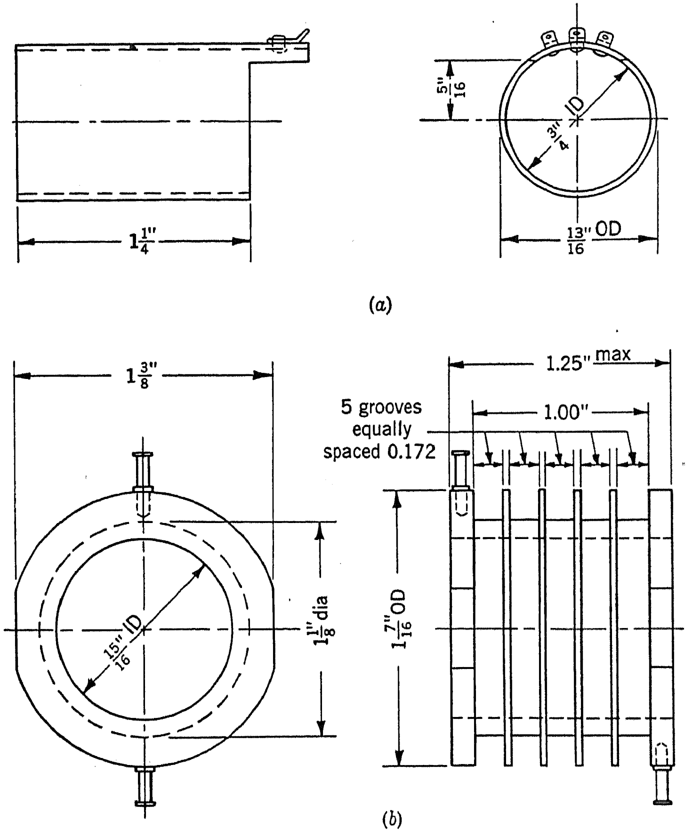


FIG. 4·20.—Primary and secondary coil forms.

former losses and size, since total losses decrease with an increase in size. Because efficiency and small size were both of importance in this application it was necessary to use low-loss core materials. The core finally chosen was a $\frac{1}{2}$-in. stack of 83 6-mil RL No. 50-EE laminations of "Carpenter 49" nickel-iron alloy, weighing 0.333 lb. The primary winding was 600 turns of No. 35 wire tapped for the plate supply at 100 turns from the grid end. It was wound on a form of linen-base bakelite tubing shown in Fig. 4·20a.

There are two possible modes of oscillation in a circuit such as that of Fig. 4·18, the second one involving a tank circuit consisting of the

primary leakage inductance in parallel with a series combination of the tank condenser and the secondary distributed capacitance as seen by the primary. This second mode of oscillation leads to unstable operation at high loads unless the leakage inductance and the secondary distributed capacitance are minimized. With the construction necessary to provide adequate insulation and low interwinding capacitance it was difficult to reduce the leakage inductance, but the secondary capacitance was considerably reduced by winding the secondary in five sections. Each section consisted of 920 turns of No. 40 wire random-wound in a groove of the bakelite coil form shown in Fig. 4·20*b*. With the voltage-doubling rectifier circuit used, the d-c output voltage of the unit was 4800 volts at a current of 500 μa.

4·4. Broadband Transformers.—The term "broadband transformers" was chosen as a designation for the subject of this section rather than the term "audio transformers" since the latter seemed unnecessarily restrictive. The essential characteristic of a broadband transformer is that it will give approximately the same performance over a comparatively broad band of frequencies, usually several decades. The design methods are essentially the same whether the unit is for a seismograph recording amplifier working from fractional cycles per second to several hundred cycles per second or for a carrier telephone circuit using a band from 1 to 100 kc/sec.

Basically the design methods for broadband transformers are the same as those for power transformers, but for any but the most uncritical applications the analysis of characteristcs must be done in more detail and attention must be paid to the problems of minimizing distributed and interwinding capacitances, leakage reactances, etc., and to maintaining accurate coil balance when push-pull windings are used. Another problem that is encountered with broadband transformers is that they must usually operate over a wide range of input signals without excessive nonlinear distortion, even though the windings may be carrying d-c currents several orders of magnitude larger than the desired signal.

The requirements for a broadband transformer are more difficult to satisfy than those for a power transformer principally because the breadth of the frequency band over which it must operate brings into direct conflict two opposing factors. At the low-frequency end of the pass band the output voltage is limited by the finite primary inductance of the transformer, and this limitation is much more serious than with the usual power transformer because of the nature of the source of power which feeds the primary. A power transformer operates from a source that may ordinarily be considered to have zero impedance, and therefore if the primary inductance is too low the only effect is an increase in the exciting current. This increase is of no moment as long as the heating

effects do not become too great. A broadband transformer, on the other hand, operates from a source of relatively high output impedance, so that any drop in the primary impedance reduces the primary voltage drop and therefore the output voltage. Transformers that work into the grid of a tube, therefore, have a response curve which falls at the rate of 6 db per octave below the cutoff frequency.

If the primary inductance is doubled by increasing the number of turns, for example, the low-frequency response curve will be shifted lower by a factor of 2 in frequency. In order to maintain the same output voltage, however, the secondary turns must be increased in the same ratio as the primary thereby doubling the secondary inductance and the leakage inductances (and perhaps seriously increasing the distributed capacitance of the secondary). As a result, the high-frequency response suffers. The net result of the change will ordinarily be a shifting of the whole frequency response curve (on a logarithmic scale) one octave to the left, without affecting its shape.

The high-frequency response of a transformer begins to fall off at a frequency at which the effects of leakage inductance and shunt capacitance become appreciable. The actual value of this frequency depends both upon the magnitudes of these quantities and upon the circuit in which the transformer is being used, but the upper cutoff for a transformer that works into a high impedance is determined principally by the properties of the transformer itself. The shape of the upper cutoff differs from that of the lower because of resonance between the effective output series inductance (which is roughly the secondary leakage inductance) and the secondary distributed capacitance. This resonance effect changes the output curve from a gradual droop such as is found at the low end, into a hump whose height depends upon the effective Q of the resonant circuit, followed by a very rapid fall, the net effect being essentially that of a low-pass filter. As with all networks where attenuation changes rapidly with frequency, the phase-shift of the transformer also changes rapidly in this region, and trouble with oscillation often results if the transformer is used in a feedback amplifier or servo loop. The resonant hump can be suppressed by various methods, such as heavy loading or winding the secondary with resistance wire, but usually at the expense of a decrease in output voltage.

The two requirements for extended low- and high-frequency response are mutually incompatible, but only to a limited extent. The low-frequency response is determined largely by the size and quality of the core and the number of primary turns. Core design is also greatly affected by the frequent necessity of permitting direct current of a magnitude several times greater than that of the signal to flow through the winding, but this can often be taken care of by a careful choice of air-gap length

and location. The high-frequency response, however, can be greatly changed by changes in the coil layout without affecting the primary inductance. Extending the bandwidth of a broadband transformer then becomes largely a matter of setting the low-frequency end by a choice of primary inductance and stretching the high-frequency end by juggling the coil layout in such a way as to decrease the capacitances and leakage inductances. A great increase in bandwidth can be obtained, but always at the expense of increasing complication of the coil with resulting increase in cost, and sometimes at a sacrifice of voltage stepup ratio.

The designer of broadband transformers seldom needs to worry about some of the factors that are of importance in power transformers. Transformer losses and heating are seldom significant except for large output transformers. Weight and size limitations are always important, but since most broadband transformers are operated at low power levels and are small enough so that the case and potting compound may weigh more than the transformer, the designer is relatively free to change core sizes, etc,. without affecting the net weight appreciably. The transformer weight is determined primarily by the power level and the low-frequency cutoff, and little can be done about it. Low operating temperatures and (usually) low voltages render the problems of insulation somewhat easier than with power transformers, but impregnation of broadband transformers must be particularly thorough since the use of very fine wire, the presence of d-c voltages, and the lack of the ability of the power transformer to bake itself out invite trouble from electrolysis.

Every transformer designer has his own "bag of tricks," depending largely upon his past experience. Some of the tricks that have been found useful in broadband transformer design are given in the following paragraphs.

One factor that reduces the effective primary inductance and increases the effective series resistance as the operating frequency is increased is the occurrence of eddy currents in the core laminations and in the conductors themselves. This effect is not usually serious with usual lamination and wire thicknesses at frequencies below about 10 kc/sec, but becomes large in the carrier-frequency range. Eddy-current losses in the core may be reduced at the expense of a reduction in the stacking factor by using very thin laminations. Losses in the windings are normally of less importance, but may be reduced if necessary by the use of very fine wire, wound with two or more strands in parallel in the same winding or in separate windings connected in parallel. Litz wire may be used in the highest frequency range.

The subdivision of windings is frequently employed for several purposes, one common purpose being to reduce the leakage inductance between two windings, as shown in Fig. 4·2. If the two sections of the

split coil are connected in parallel it is essential that they should have exactly the same number of turns, and this must be impressed upon the coil winder. In commercial coil manufacture it is customary to assume that a variation of a few turns in a winding of thousands of turns is of no importance; this assumption is true in most cases, but decidedly not true in all. If the parallel halves of a winding do have the same number of turns the effect of the circulating current that flows between them will be to buck out the leakage flux and in effect to force more of the total flux to flow through the core; if the numbers of turns are not equal the opposite effect will occur. This is particularly true if the two sections of the winding are widely separated, either in the same coil or on opposite core legs. The effect is analogous to the third-harmonic cancellation produced by the circulating current in a delta-connected 3-phase transformer bank.

Another beneficial effect of subdividing windings is that a reduction of distributed capacitance may be obtained with a resulting displacement of the secondary resonant peak. Certain carrier transformers depend upon this method to hold up the response out to several hundred kilocycles per second. In effect the subdivision of the secondary subdivides the resonant peak, and by a suitable choice of the resonant frequencies of the individual portions of the winding the individual resonant peaks of the sections are spaced over the frequency range. The amplitude of the alternating peaks and valleys may be reduced by proper secondary loading and by the use of high-resistance secondary windings. The resultant copper losses are usually unimportant except for high-level output transformers.

Interwinding capacitances can be effectively eliminated by the interposition of a copper-foil shield, connected either to ground or to some other appropriate point in the circuit. Such shields, however, increase the capacitance of the windings to ground. Another type of shield that is sometimes useful is an eddy-current shield of heavy copper sheet placed directly over the core tube. If a fairly wide insulated lap joint is used this shield will not affect the main flux that passes through the core but any radial component of the flux will induce opposing eddy currents in the shield, which will effectively force all the flux to pass through the core. This type of shield is particularly useful on long thin cores and on such units as that shown in Fig. 4·15. Its effectiveness decreases rapidly at low frequencies.

If the best possible performance is desired from transformers having balanced inputs and outputs some care must be given to maintaining accurate resistance and capacitance balance between the halves of the windings. The easiest and most effective way of doing this is to maintain geometrical symmetry between the halves, so that they are physically

identical, but if this cannot be done, as when one half of a push-pull secondary is wound on top of the other half, it may be necessary to wind the inner portion with smaller wire to maintain the resistance balance, and to juggle the numbers of layers and the turns per layer to keep the distributed capacitance the same for the two halves.

Both distributed and interwinding capacitances can be somewhat reduced by the use of insulating materials and impregnants of low dielectric constants. Certain waxes are available which have constants appreciably lower than the usual varnishes, and styrene-base impregnants have still lower constants. It is to be hoped that further progress in the development of insulating materials will result in further reductions.

The maintenance of sufficiently high inductance as the over-all size of the unit is reduced depends upon the use of materials of very high permeability and of core constructions with very-low-reluctance joints. The method of stacking described in connection with Fig. 4·11*b* is often helpful in this connection. In addition, if the inductance is to be maintained at very low power levels it is essential that the core material have high initial permeability; this requirement rules out the use of some silicon steels and demands such materials as 78 Permalloy.

CONSTRUCTION OF IRON-CORE INDUCTORS

4·5. Cores.—The great improvement that has taken place in the last thirty years or so in the characteristics of transformers and similar devices has been due in large part to the development of better magnetic core materials, and this development has been particularly rapid during the last decade. Many materials, moreover, that were developed prior to that period, have only recently become generally available, so that today there is a much wider choice of improved magnetic alloys, both hard and soft, than were on the market even in the 1930's.

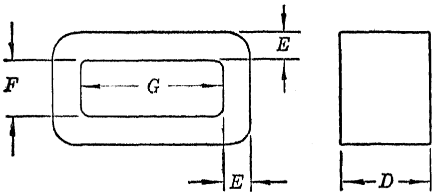


FIG. 4·21.—Radiation Laboratory standard Hipersil cores.

The core materials that were most extensively used for transformers and chokes by the Radiation Laboratory were Westinghouse "Hipersil," Allegheny "4750," and Magnetic Metals Company "Carpenter 49" alloy. Hipersil is a grain-oriented silicon steel which is furnished in the form of complete core assemblies, each core consisting of two C-shaped halves. A series of 20 such Hipersil cores was standardized by the Laboratory for its own use and all of its designs for such a form of core were based on one or another of these sizes. The standard Hipersil cores are shown in Fig. 4·21 and their dimensions are given in Table 4·3.

The Allegheny "4750" and the "Carpenter 49" are nickel-iron alloys, and were employed for the most part in the form of E-I laminations stamped from 6-mil sheet. The E-I stampings used in most commercial transformers are of the so-called "scrapless" type, which is designed for the minimum loss of material in stamping rather than for magnetic efficiency. J. P. Woods[1] has shown that the most efficient lamination shape at any frequency at which the iron can be worked at its maximum

TABLE 4·3.—HIPERSIL CORE DIMENSIONS

Core No.	Dimensions of finished core, in.				Lamination thickness, in.
	D	E	F	G	
1	$\frac{5}{8}$	$\frac{1}{4}$	$\frac{1}{2}$	$1\frac{1}{16}$	0.013
2	1	$\frac{5}{16}$	$\frac{5}{8}$	$1\frac{9}{16}$	0.013
3	$1\frac{1}{4}$	$\frac{3}{8}$	$\frac{5}{8}$	$1\frac{15}{16}$	0.013
4	$1\frac{1}{4}$	$\frac{1}{2}$	$\frac{5}{8}$	$1\frac{15}{16}$	0.013
5	$1\frac{1}{2}$	$\frac{3}{8}$	$\frac{15}{16}$	$2\frac{1}{2}$	0.013
6	$1\frac{1}{2}$	$\frac{1}{2}$	$\frac{15}{16}$	$2\frac{1}{2}$	0.013
7	$1\frac{1}{2}$	$\frac{1}{2}$	1	3	0.013
8	2	$\frac{1}{2}$	1	3	0.013
9	2	$\frac{11}{16}$	1	3	0.013
10	2	$\frac{3}{4}$	$1\frac{3}{8}$	3	0.013
11	$\frac{3}{4}$	$\frac{3}{16}$	$\frac{1}{2}$	$1\frac{1}{8}$	0.007
12	$\frac{7}{8}$	$\frac{7}{32}$	$\frac{1}{2}$	$1\frac{1}{2}$	0.007
13	1	$\frac{1}{4}$	$\frac{1}{2}$	$1\frac{1}{2}$	0.007
14	1	$\frac{9}{32}$	$\frac{5}{8}$	$1\frac{9}{16}$	0.007
15	$1\frac{1}{8}$	$\frac{5}{16}$	$\frac{5}{8}$	$1\frac{11}{16}$	0.007
16	$1\frac{1}{4}$	$\frac{3}{8}$	$\frac{5}{8}$	$1\frac{15}{16}$	0.007
17	$1\frac{1}{4}$	$\frac{5}{16}$	$\frac{3}{4}$	$2\frac{5}{16}$	0.007
18	$1\frac{1}{2}$	$\frac{3}{8}$	$\frac{3}{4}$	$2\frac{5}{16}$	0.007
19	$1\frac{1}{2}$	$\frac{3}{8}$	$\frac{15}{16}$	$2\frac{1}{2}$	0.007
20	$1\frac{1}{2}$	$\frac{1}{2}$	$\frac{15}{16}$	$2\frac{1}{2}$	0.007

permissible loss value is that shown in Fig. 4·22. A series of laminations similar to this but with a slight compromise toward lessened scrap loss, was developed by the Radiation Laboratory. The dimensions of these laminations are shown in Fig. 4·23. Both the laminations and the Hipersil cores were very useful and allowed efficient designs to be worked out. The use of these improved materials and designs permitted a reduction in transformer weight of approximately 50 per cent, although the

[1] J. P. Woods, "Principles of the Design of Small Power Transformers," RRL Report No. 411-78, Jan. 25, 1944.

better core materials cost from five to ten times as much per pound as the older silicon steels in scrapless lamination form.

Some idea of the way in which these improved magnetic materials compare with older steels can be obtained from the characteristic curves

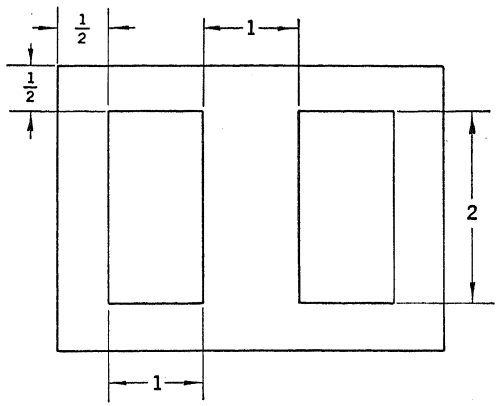


FIG. 4·22.—Most efficient lamination shape.

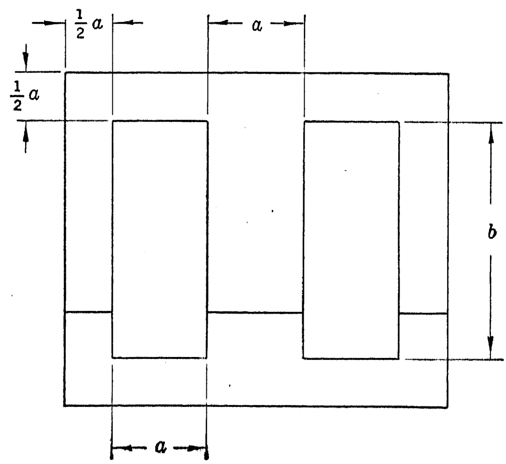


FIG. 4·23.—Radiation Laboratory standard nickel-iron laminations.

given in the next three figures. Fig. 4·24 shows the magnetization curves for two thicknesses of Hipersil (labeled 13HIP and 5HIP, the figures referring to the thickness in mils), a nickel-iron alloy such as Allegheny "4750" (labeled Ni-Fe), and two of the older silicon steels, a low-loss type, A, and a high-loss type, SD. It can be seen that the nickel-iron alloy saturates much more sharply and at a much lower magnetizing force than do the other alloys, but that its saturation flux density is about the same as that of all the others except the 13HIP. The 5HIP is much like the A and SD, although its permeability is slightly higher,

but the 13HIP curve is still rising rapidly at an H-value of 18 ampere-turns per inch, at which it has reached a flux density about 50 per cent higher than the saturation value for the other materials. The difference

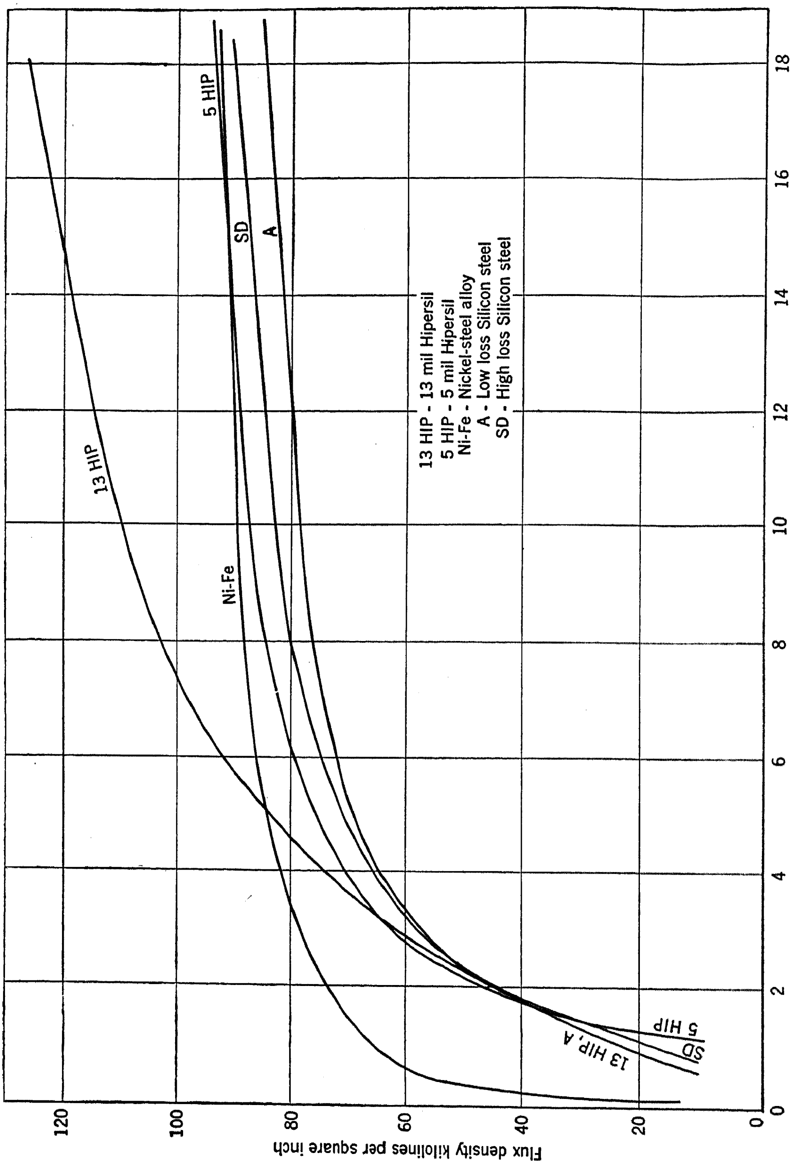


FIG. 4·24.—Magnetization curves of transformer core materials.

in form between the 5HIP and 13HIP curves is striking, since the material has the same composition in the two cases, and differs principally in the metallurgical treatment it has received.

Figs 4·25 and 4·26 show core-loss curves at 60 and at 400 cps for three materials in each case. At 60 cps and the standard Epstein Test density of 10,000 gauss (64.5 kilolines/in.^{2}), for example, the total core loss for 13HIP is only 0.35 watts/lb, compared to about 0.65 for A and 0.90 for the high-loss SD. The same type of improvement is shown at 400 cps

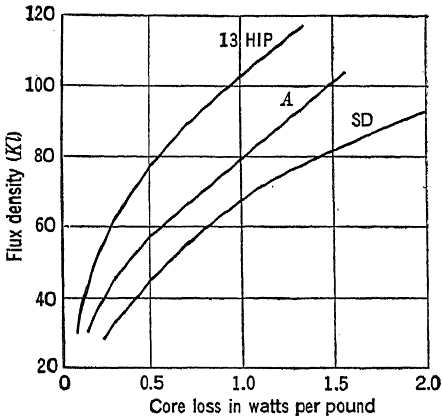


FIG. 4·25.—Core loss at 60 cps. (Flux density is in kilolines/in.^{2})

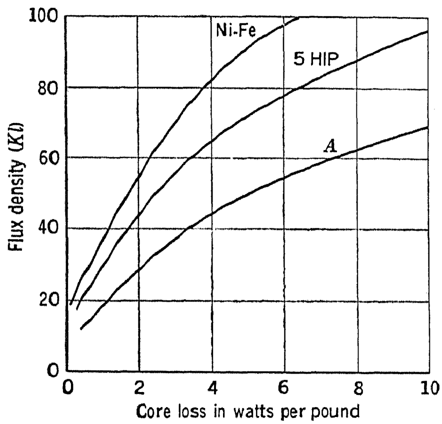


FIG. 4·26.—Core loss at 400 cps. (Flux density is in kilolines/in.^{2})

by the new materials; at 10,000 gauss the losses for A and for 5HIP are about 8.5 and 4 watt respectively, whereas for Ni-Fe they are only about 2.6. Since the most efficient transformer is one whose copper losses equal its iron losses, so that decreased iron losses in a sense force a reduction in copper losses, it can be seen that improved core materials permit a transformer to run much cooler; or conversely, they permit a much smaller transformer to be built for the same temperature rise. The

steady improvement of magnetic materials has by no means stopped, and still further improvements may confidently be expected.[1]

4·6. Coils. *Magnet Wire.*—Although the advances in core-material manufacture have somewhat overshadowed those in other fields of the transformer art, they are by no means the only improvements that have been made recently. One of the outstanding developments that has taken place in the last few years has been the introduction of a number of new insulating materials, and of these one of the most important is polyvinyl acetal wire insulation, usually called Formvar, or its GE trade name, Formex.

Before the introduction of Formvar, the manufacturer of electrical windings had two principal types of wire insulation to choose from, fibrous wrappings of various types, or oil-base enamels. The fibrous insulations suffer from a number of disadvantages, the chief of which is the poor space factor of fibrous-insulated wire especially in the smaller sizes. In addition this type of wire is more expensive, both on a per pound and a per foot basis, it is stiffer and harder to wind because it springs back during the winding process and produces an open coil with a poor build factor, and fibrous insulations (except Fiberglas) are much more hygroscopic than other types. Oil-base-enamel wire insulation is greatly superior to fibrous insulation in these respects, but there are many applications for which it is not suited because of its relative sensitivity to abrasion or its poor resistance to the attack of certain chemicals.

The introduction of Formvar has furnished the coil manufacturer with a wire insulation that is similar to enamel in its electrical properties but is greatly superior mechanically and chemically, is more uniform, and stands high temperatures much better. Its chief advantage is its abrasion resistance, which is from three to twenty times that of enamel, depending upon the method of measurement. The abrasion resistance and other properties of Formvar are much less affected by high temperatures than are those of enamel. Another important property is its resistance to attack by chemicals, particularly some of the common solvents used in impregnating varnishes. The use of oil-type-enamel wire insulation in a coil severely limits the choice of the varnish, and this limitation often results in the use of fibrous-insulated wire in spite of its disadvantages. Formvar, however, is attacked only by phenols and cresols and by certain mixed solvents containing both alcohol and aromatic hydrocarbons, so that almost any impregnant may be used with it.

The coating is applied to enameled wire by passing the wire through

[1] This prediction, written early in 1946, has already come true. See O. L. Boothby and R. M. Bozorth, "New Magnetic Material of High Permeability," *Jour. Applied Phys.*, **18**, 173–176 (February 1947), for a brief discussion of the new alloy Supermalloy.

a bath of the enamel dissolved in a solvent, thence upward out of the liquid through a die which in effect draws the liquid film down to the correct thickness, and up through a high vertical oven in which the solvent is evaporated and the enamel hardens. Since the evaporation of the solvent and the initial hardening of the enamel require time and since the wire cannot be allowed to touch anything until the coat has hardened sufficiently, the linear speed of the wire through the coating machine is severely restricted. This restriction considerably increases the cost of production, and if the speed is injudiciously increased the coating is scarred by contact with pulleys or guides before it has hardened sufficiently. Other variables, such as change of viscosity or composition of the bath, affect the thickness and regularity of the coating. One not uncommon fault of enamel coatings is the beaded wire illustrated in Chap. 8, Fig. 8·3. In applications such as the precision potentiometers of that chapter, in which uniformity of wire dimensions is essential, such defects may be serious.

Formvar may be applied by a similar process, but since it is thermoplastic it may also be extruded on to the wire in the same way that larger wire and cable is jacketed. As a matter of fact, "vinyl" cable jackets and insulations for various types of wires are made of essentially the same material as Formvar, and have the same desirable properties. (See Chap. 1 for more data on the material.) The extrusion process results in a wire with a uniform, tough, highly adherent coating. This type of insulation is coming more and more into use as its merits become known. It is displacing fibrous insulations, in the smaller sizes at least, for all applications except those involving the most severe abrasion, and it is replacing enamel where its better mechanical and chemical properties are of importance. It will never wholly replace either, but it does greatly assist the coil manufacturer to turn out a better product.

Interlayer Insulation.—Relatively less improvement has taken place in the field of interlayer and miscellaneous insulations, but here also there are a number of new and improved materials. Most transformer coils still rely largely upon various forms of paper for interlayer and interwinding insulation, core tubes, and wrappers, and this situation is unlikely to change materially in the near future. There has been improvement in the properties of electrical papers, chiefly in the direction of greater purity and uniformity and the use of better impregnants, and some new materials have appeared. Probably the most important class of new material is the Fiberglas products, such as cloth, string, tape, and sleeving. Fiberglas textiles are very strong and chemically inert, and are immune to any rise of temperature likely to occur in an electrical winding, but are harder to handle and are not as resistant to flexing and abrasion as organic textiles. They may be impregnated with the same

varnishes as are used on organic textiles, or silicone varnishes may be used to permit operation at high temperatures. Fiberglas textiles are often used unimpregnated if sealing or the prevention of fraying are not necessary. Silk has almost vanished from the electrical field because of wartime scarcity and the inroads of Formvar on the fine-wire field, but synthetics such as rayon have replaced it. In particular an acetate-rayon tape introduced in 1944 proved to be greatly superior to varnished cambric for the work of the Radiation Laboratory. It is more flexible, lies in place better, especially on an uneven surface, and has about 30 per cent higher breakdown strength for the same thickness. Braided sleeving is still largely used for the insulation of coil leads, but in some cases extruded tubing (usually of the ubiquitous vinyl plastics) may be preferable. Synthetic sheets of various materials may be useful, but so far either inferior electrical properties or low softening temperatures have prevented extensive application in the transformer field. This is particularly true of cellophane, which is poor electrically, and nylon, which does not stand high temperatures. With the present intense activity in the field of synthetic plastics, however, this situation may change.

The Winding Process.—The construction of the conventional paper-layer-insulated coil starts with the core tube. This is a rectangular tube of spirally wound layers of paper or other suitable material, whose inside dimensions correspond to the core width and thickness. Core tubes may be bought from dealers in electrical or paper specialties, or they may be made by the user by winding ordinary gummed kraft paper tape, such as is used for sealing cartons, around a suitable rectangular mandrel of metal or hard wood. The mandrel must be smooth and free from nicks and ridges or it will be impossible to remove the finished tube. A layer of tape is first applied in a helix with the gummed side out and the edges just butting, with no appreciable gaps or overlaps. Additional layers are then added in the same fashion, the gummed side being inwards and being moistened before winding, and the center of each layer coming directly above the joint of the previous layer. For most work the tube can be used as wound; if additional insulation is required it may be added when the core tube is being wound or before winding the coil. The thickness of the wall depends upon the size of the coil; for small radio transformers it should be from five to seven layers of 7-mil kraft.

The mention of gummed kraft paper brings up one precaution that applies not only to it but to everything that goes into the makeup of a coil. If materials are bought from a reputable electrical dealer it may be safely assumed that they are suitable for electrical uses. This is not the case with apparently similar materials bought elsewhere; they may be perfectly suitable for their intended purpose but still capable of causing

serious trouble in a coil. Some gum compositions and some papers, for example, contain constituents that may cause serious trouble from corrosion of fine-wire windings. This is particularly true of scotch tape; electrical scotch tape is perfectly satisfactory for anchoring coil ends, if used in moderation, and if not used in oil-immersed coils, but some grades of cheap masking tape of identical appearance are highly corrosive to fine wire. It is poor economy to use substitute materials of unknown characteristics either in laboratory models or in production.

The actual technique of winding a coil depends largely upon the type of winding machine used. It is possible to wind coils in a lathe, and thousands are so wound in the absence of a regular winding machine, but the patience of Job is required for the task if the coil includes high-voltage windings of fine wire. It will be assumed accordingly that a simple winding machine is to be used, which has accurate adjustments for winding pitch, adequate wire-tension controls on the feed spools, and at least a rudimentary paper feed and cutoff knife. Such a machine should be part of the equipment of any shop or laboratory that must wind more than a very few transformers; quantity manufacturers use considerably more elaborate machines with multiple paper feeds, instant-change preset winding pitch control, and other desirable—and expensive—features for speeding up production.

The first operation in winding a coil is to fasten the inside end. The amateur coil winder will probably start by making and taping a soldered joint between a stranded hookup wire lead and the enameled wire of which the coil is to be wound. This method is satisfactory—except for two things. If this joint, or even the inner end of the hookup wire insulation, comes inside the coil structure it will make a bump that will render it difficult to do a smooth winding job, and the same thing applies to all successive coil ends. Furthermore, unless the coils are being wound one at a time, which is seldom the case in commercial work, there is no place to put the wire lead while the coil is being wound.

The professional winder starts by winding a half-dozen turns in the coil margin and then moves in to the actual start of the coil. He lays a bit of tape, adhesive or otherwise, under the start of the first turn, sets his turn counter to zero, and winds one turn. Just before completing the turn he folds the outer end of the bit of tape over the starting end of the wire and catches it under the end of the first turn. He then starts his drive motor and proceeds to wind the coil. "Finish" ends are similarly secured except that since the anchor tape cannot be held down by the next-to-last and preceding turns it must be fastened by an adhesive. Some winders use heavy shellac and cover the anchor tape and the whole side of the coil with a strip of kraft paper shellacked in place. A professional, moreover, will not bring out the coil leads on a

side of the coil which is to be covered by a leg of the core; apparently every amateur has to try this at least once, preferably on a coil of many thousands of turns. After anchoring the finish turn the winder will add a few turns in the margin before cutting the wire and starting the next coil. If the required number of turns in a winding is not such as to give an integral number of layers (which is invariably the case in practice) there are three possibilities. The number of turns per layer may be somewhat reduced to give an integral number of layers, and the winding pitch increased to maintain the correct margins; this is the professional solution, and the professional coil designer will include the number of turns per layer in his winding specifications. The winding pitch may be sufficiently increased to stretch the last layer over the allotted space; this can only be done if the deficiency in the last layer is not too great, and requires an extra time-consuming pitch adjustment. A filler can be used; this is sometimes done on filament windings that only occupy one- or two-and-a-fraction layers and which are usually wound one at a time. Often in the last case a better solution is to use a different wire size in order to fill the space, if this can be done.

In winding the coil the professional winder using a nonautomatic machine will keep track of the number of turns he has wound and will slow down smoothly near the end of each layer, stopping just as the limit switches reverse the feed clutches. He will feed paper from the roll out to the coil mandrel, catch it under the wire as it feeds on to the coil, turn the mandrel a fraction of a turn by hand to anchor the paper, and then operate the paper cutoff knife and continue with the next layer. The skilled winder will do this without actually stopping the machine, particularly if he is on piece work. The paper should be so caught and cut off that the lap comes outside the core window, and the lap should preferably be alternated from one side of the coil to the other. If this is not done with fair consistency the excessive number of laps will cause the window side of the coil to build out too fast and the coil will come out too large to go in the window.

Succeeding windings are put on the coil in the same way as the first winding, the winding pitch adjustment, and if necessary the paper roll, being changed between windings. In production of small transformers as many coils are wound at a time as will go on a "stick," whose length is determined by the width of the paper roll used. Since adjustments and machine changes are time-consuming a winder will ordinarily wind all of the inner coils for a job with a single setup a stick at a time, then reset the pitch adjustment and wind all of the second windings, etc. Heavy-wire windings, such as filament and low-impedance loud-speaker windings, are usually put on the outside of the fine-wire windings and are wound by hand, one at a time. Heavy-wire leads are usually con-

tinuations of the winding itself, additional insulation being furnished by sleeving if necessary.

After completing the windings the stick of coils is cut apart. This process may be done on the winding machine by means of safety-razor blades held in a frame that can be swung down so as to bring the blades in contact with the slowly rotating stick, in which case the mandrel must be grooved to permit the blades to cut clear through the coils and into the core space, or the stick may be cut apart after removal from the mandrel. Circular saws may be used for this purpose, in which case they should be in the form of knives with scalloped edges, or straight-edged band knives may be used. The most effective device is a bandsaw fitted with a sliding V-block to hold the stick and using a wavy-edged knife made by the saw manufacturers for bread-slicing machines. This form of cutter gives a clean cut with much less tearing and friction than the circular knife, and cuts much truer than a straight-edge band.

Finishing.—After the coils are wound they must be finished; leads must be brought out and anchored, wrappers or lug strips applied, and all other operations prior to the core assembly completed. As has been stated, the leads of heavy-wire windings are usually continuations of the windings themselves, with insulating sleeving if necessary. The single-winder adds a few turns in the coil margins to form the leads, just as the machine-winder does, but the ends of heavy-wire leads are easy to find and to bring out for termination. Frequently the single-winder will also add the insulating sleeving. The coil finisher, who must also be furnished with the coil specification sheet, digs out the coil ends of the fine-wire windings from between the paper layers, using a pointed or slightly hooked tool for the purpose (a nutpick is a favored implement) and makes sure that all of the extra turns are pulled out clear down to the end-turn anchorage. These wire ends are then led radially outward along the end of the coil, cut off to the proper length, bared, tinned, and soldered to the flexible leads or to the solder lugs of the lug strip if one is used.

The coil leads must be securely anchored, the method of anchoring depending somewhat on circumstances. Usually the leads are carried across the face of the coil, a turn or two of strong tape is wound over them, the leads are brought back over the tape, and another turn or two is added. The exposed radial portions of the coil ends are insulated by strips of paper, or for the higher voltages by varnished silk or cambric held in place by a suitable adhesive. The final operations are the addition of the outer heavy coil wrapper and the marking of an identification number on the wrapper. The coil is now complete except for impregnation, which may be done either before or after inserting the core. Impregnation will be discussed in Sec. 4·7.

Probably the best way to become acquainted with the techniques of

coil winding and finishing is to visit a transformer plant; if this is impractical a great deal may be learned by the careful dissection of a few discarded transformers, preferably those of a maker with high quality standards.

Other Types of Windings.—Next to paper-insulated layer windings the most-used type is the so-called "random" winding, in which the wire is simply wound back and forth in the groove of a coil form until the required number of turns has been wound. In commercial practice the term "random" is somewhat inappropriate, since the wire is put on in a regular pattern that somewhat resembles that of a universal winding, although the winding is not an open one. The wire is wound as in a layer winding but with a winding pitch several times the wire diameter, so that the turns of one pass fall at nearly the same average radius as those of the previous pass and not into definite layers. No insulation is used within the coil except that of the wire itself. Random windings are difficult to make on any except a round core, and are chiefly used for loud-speaker field coils, relay coils, etc. For such purposes they are very satisfactory, and they are cheap to make. Random-wound coils differ from most others in not being self-supporting, so that some sort of bobbin or form is required. This form may be molded from a suitable plastic, and such molded bobbins are often used on very small coils for which layer insulation is impractical. Bobbins may also be fabricated from laminated plastic tubing with laminated sheet plastic ends. The principal difficulty with this form of construction is preventing the ends from coming off, especially if the coil is wound by hand and therefore is truly random. Commercial random-wound coils are often wound on flimsy bobbins made of heavy gummed kraft paper, the bobbin being supported during the winding process by a suitable form that can be taken apart later. If the wound coils are not roughly handled the paper bobbin will support them long enough to permit the coil finisher to anchor the flanges in place with an outer wrapper of light gummed paper that is later reinforced by heavier end pieces and a final heavy wrapper. If the coil is too large or of too fine wire to permit the use of the paper bobbin alone it may be held together by strips of tape inserted in a U-shape before the winding is started and having the ends fastened before removing the supporting outer form. In either case the coil will be rugged enough after impregnation to withstand considerable mechanical abuse.

One type of winding beloved of the amateur coil winder but rarely used in production because of its high cost is the uninsulated layer winding. It may be wound on an ordinary lathe, and may or may not use a bobbin. If it does not it is somewhat easier to wind but wastes some space at the ends. It may be wound by feeding the wire into place by hand, but the process is slow and some kind of glove or other protection

for the hand, although awkward, is absolutely necessary. Such windings may be made of enamel- or Formvar-coated wire, but fibrous-insulated wire is preferable because it is less slippery and stays in place better. It is also far more abrasive.

In making an uninsulated layer winding on a lathe it is best to mount a guide pulley on an arm in the tool post, taking care not to have it too close to the surface of the coil, and to set the feed to approximately the winding pitch required, or preferably slightly less. An adequate adjustable smoothly operating brake on the wire spool, controlled by the wire tension, is almost a necessity, as is a smooth control of the spindle torque. This may be obtained from a series motor and foot rheostat, or foot switch and Variac, or by a foot-controlled tight-and-loose pulley arrangement with the belt slack enough to permit some slipping.

The compound rest is set to move the guide pulley parallel to the ways of the lathe and is used to correct for the inequality between the winding pitch and the feed. The guide pulley should be allowed to lag slightly behind so as to ensure that the wire will be truly close-wound without any spaces, especially on the first layer. If a bobbin is used the layers should be wound full, but it is inadvisable to try to force an extra turn into place at the end of a layer because this will cause an excessive pressure on the bobbin flanges and is also likely to result in an irregularity that will propagate itself to all succeeding layers. If no bobbin is used the ends of each layer may be held in place with bits of tape as described previously, about four pieces being used per layer end. The tapes should be staggered and the thinnest possible material used to prevent building out the coil ends.

The uninsulated layer winding has an excellent space factor if properly made, but is maddeningly slow to wind and is impractical for fine wire. It should be used only when a better method is not available.

Another type of coil which is intermediate in character between a random and a regular layer winding is the so-called "string-wound" coil. It has been used principally for the coils of power contactors, although the old Giblin-Remler honeycomb coils and some Western Electric transformers were also string-wound. The winding consists of uniform close-wound layers of wire, as in a paper-insulated winding, but instead of the paper a very open universal winding of small yarn or string is used. The turns of yarn cross the wire turns at a large angle and the yarn guide pauses for an instant at each end of its stroke to allow the yarn to build up a protective margin. The resulting coil is dense and solid, even before impregnation, and has a good space factor. With the newer materials such as Fiberglas yarn, Formvar wire insulation, and silicone varnish impregnation string winding should be an excellent method of coil construction.

Another type of winding which has found its principal application in transformers for high voltage or high powers, is the pie winding. This may take either of two forms. In one, the conductor is usually a thin wide rectangular strip that is wound into flat spiral pies one turn thick in the axial direction. The pies are stacked on the core and connected in series. One disadvantage of this construction is the large number of series connections that must be made. Allis-Chalmers uses an ingenious method of construction in which pairs of pies are wound from a single length of conductor, thus eliminating the inner connections. The other type of pie winding consists of thin random-wound pies of fine wire, either wound in deeply grooved bobbins or individually taped, and again connected in series. The voltage per pie is limited to that which the wire insulation will stand, times the average number of layers per pie. This construction has been used chiefly for the high-voltage windings of X-ray transformers.

A rare construction that can occasionally be used for high-current chokes and the like employs a spiral winding of copper foil or sheet, of a width equal to the axial length of the coil less the necessary margins, insulated with paper or other suitable material, the whole coil being similar in construction to a wound foil-and-paper condenser. This construction has the advantage of a good space factor and excellent heat conductivity, especially in the axial direction, but is difficult to wind and to impregnate. It might be useful for low-voltage windings.

TABLE 4·4.—COPPER ALLOWANCE FOR SMALL TRANSFORMERS

Rating, va		Copper allowance, circular mils/ampere
60 cps	400 cps	
0– 10	0– 25	400
10– 50	25– 100	800
50– 150	100– 300	1000
150– 500	300– 750	1200
500–1500	750–1500	1500

There are many other possible types of windings, but they are too rare to be worth describing in detail. For small inductors such as those with which this chapter is concerned, constructions other than the paper-layer-insulated and the random-wound types seldom need be considered.

Coil Design Data.—The data to be given here apply primarily to the paper-insulated layer winding because it is by far the most important type of transformer winding. Additional data may be obtained from the manufacturers of wire, winding machines, coils, and equipment in which coils are used.

The first operation in designing a coil is to select the wire size for each winding on the basis of the operating current for that winding. Table 4·4 gives suitable values for the copper allowance for the windings of small transformers of usual construction and mounting practice. The tabulated values of circular mils per ampere will result in approximately a 40°C rise in temperature under ordinary conditions; if a different rise is desired the area should be changed accordingly.

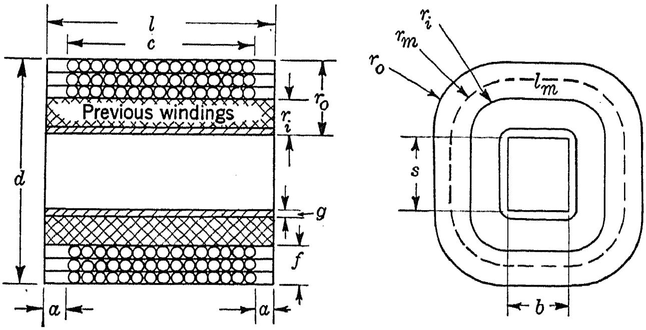


FIG. 4·27.—Dimensions of layer-wound coil. $r_m = \frac{r_o - r_i}{2} = \frac{nd_w + (n-1)t_i}{k_b}$; $l_m = 2(b + s + \pi r_m)$ = length of mean turn; f = build of winding; n = number of layers; d_w = OD of wire; t_i = thickness of interlayer insulation (this must be multiplied by a constant to allow for lapping: for $\frac{1}{4}$ turn lapping the constant is about $\frac{5}{4}$); k_b = build factor = 0.85 for average construction (see text).

It will often be found that the wire size required for heavy-current or low-impedance windings is too stiff to wind easily on small coils. In such cases stranded wire may sometimes be used at the expense of a serious reduction in space factor, but a better expedient is to make the winding of two wires of half the area, wound side by side and connected in parallel at the ends. Even more than two strands may be used in special cases, although it is difficult to control more than two at a time if the wire is fed by hand.

A typical layer-insulated coil is shown schematically in cross section in Fig. 4·27, and certain quantities that are useful in designing a coil are listed below the figure. A winding table, modified from the one used at the Radiation Laboratory, is given as Table 4·5. This table includes data on single-coated and heavy-coated wire only, since other forms of insulation are less important for small transformers. The data apply to both enamel and Formvar coatings since they are made to almost identical dimensions. The bare-wire dimensions given apply to wire of the nominal diameter; the standard diameter tolerance is ± 1 per cent of the diameter. Similar data on wire with other insulations may be found in the catalogues of the wire manufacturers and in engineering handbooks. The values of turns per inch are obtained by multiplying the theoretical number of

TABLE 4·5.—WINDING TABLE FOR PAPER-INSULATED LAYER WINDINGS

AWG size number	Bare wire				Single-coated wire (*E* or *F*)	
	Nominal diameter, mils	Area, circular mils	Resistivity at 20°C, ohms/1000 ft	Lb/1000 ft, nominal	Maximum diameter, mils	Turns/in.
10	101.9	10,384	0.999	31.4	105.4	9
11	90.7	8226	1.261	24.9	94.1	10
12	80.8	6529	1.588	19.8	84.0	11
13	72.0	5184	2.001	15.7	75.0	12
14	64.1	4109	2.524	12.4	62.0	14
15	57.1	3260	3.181	9.87	59.8	15
16	50.8	2580	4.020	7.81	53.4	17
17	45.3	2052	5.054	6.21	47.7	19
18	40.3	1624	6.386	4.92	42.6	22
19	35.9	1289	8.046	3.90	38.1	24
20	32.0	1024	10.13	3.10	34.1	27
21	28.5	812.3	12.77	2.46	30.5	30
22	25.3	640.1	16.20	1.94	27.3	34
23	22.6	510.8	20.30	1.55	24.4	38
24	20.1	404.0	25.67	1.22	21.8	42
25	17.9	320.4	32.37	0.970	19.5	47
26	15.9	252.8	41.02	0.765	17.4	52
27	14.2	201.6	51.44	0.610	15.6	59
28	12.6	158.8	65.31	0.481	14.0	66
29	11.3	127.7	81.21	0.387	12.6	73
30	10.0	100.0	103.7	0.303	11.2	82
31	8.9	79.21	130.9	0.240	10.0	91
32	8.0	64.00	162.0	0.194	9.1	101
33	7.1	50.41	205.7	0.153	8.1	114
34	6.3	39.69	261.3	0.120	7.2	128
35	5.6	31.36	330.7	0.0949	6.4	142
36	5.0	25.00	414.8	0.0757	5.8	158
37	4.5	20.25	512.1	0.0613	5.2	174
38	4.0	16.00	648.2	0.0484	4.7	198
39	3.5	12.25	846.6	0.0371	4.1	220
40	3.1	9.61	1079	0.0291	3.7	246
41	2.8	7.84	1323	0.0237	3.3	274
42	2.5	6.25	1659	0.0189	3.0	304
43	2.2	4.84	2143	0.0147	2.7	340
44	2.0	4.00	2593	0.0121	2.4	369

TABLE 4·5.—WINDING TABLE FOR PAPER-INSULATED LAYER WINDINGS.—(*Continued*)

AWG size number	(HE or HF) Maximum diameter mils	(HE or HF) Turns/in.	Layer space factor, per cent	Minimum interlayer insulation thickness, mils	Minimum margin, inches
10	107.1	9			
11	95.7	10			
12	85.5	11		0.010	
13	76.5	12			
14	68.4	14			$\frac{1}{4}$
15	61.2	15			
16	54.8	17			
17	49.1	18		0.007	
18	44.0	21	90		
19	39.4	23			
20	35.3	26			
21	31.6	29			
22	28.4	33		0.005	
23	25.5	36			$\frac{3}{16}$
24	22.9	40			
25	20.6	44			
26	18.5	49			
27	16.5	56		0.003	
28	14.9	62	89		
29	13.4	69			
30	12.0	77			
31	10.8	84			
32	9.8	94	88	0.002	
33	8.8	105			
34	7.8	115			
35	7.0	130			$\frac{1}{8}$
36	6.3	146			
37	5.7	159	87	0.001	
38	5.1	182			
39	4.5	200	86		
40	4.0	227			
41	3.6	251		0.0007	
42	3.2	285	85		
43	2.9	317			
44	2.7	328			

turns per inch (i.e. the reciprocal of the nominal outer diameter of the wire in inches) by the appropriate layer space factor. This factor is intended to take care of normal variations in wire diameter and of kinking and springing of the wire during the winding process. The values given for the factor are conservative; if necessary a few per cent more turns can usually be crowded into a given space than the figures of the table would indicate, but it is not always safe to depend upon doing so.

For large transformers and for windings carrying heavy currents it is sometimes desirable to use square or rectangular wire in order to improve the space factor of the coil. Such wire is available in a large number of sizes and with various insulations, of which double cotton and heavy Formvar are standard. Square wire may be obtained from 64-mil diameter upwards and rectangular wire from 100 mils wide and 12 mils thick. Such wires are seldom needed for small coils but for large units and especially for pie-wound coils they are much easier to handle than round wire.

Wires smaller than No. 40 are usually avoided wherever possible because of the difficulty of handling the very small sizes on the usual types of winding machines. They are rarely specified by AWG size, the diameter in mils being preferred. The usual sizes are:

2.8 mils	(No. 41)
2.5	(No. 42)
2.2	(No. 43)
2.0	(No. 44)
1.75	
1.25	
1.00	

An idea of the fragility of the ultrafine sizes may be obtained from the fact that the insulation thickness of 1-mil wire is 0.1 to 0.2 mils, its breaking strength is 14 grams, and it runs 51 miles to the pound.

Besides the wire dimensions, Table 4·5 includes data on the thickness of interlayer insulation and on coil margins. These data are based on the mechanical requirements of a rugged coil; both margin width and insulation thickness must be sufficiently great to withstand the operating voltage gradients; therefore the values given in the table may have to be increased for electrical reasons. A safe value for the maximum permissible voltage gradient along the surface of dry or varnish-impregnated paper is 10 volts per mil, which may be increased to 30 volts per mil for oil-immersed coils. These gradients refer to the test voltage, which may be variously specified. One typical specification[1] requires a test voltage

[1] Proposed Joint Army-Navy Specification JAN-T-27, "Transformers and Inductors (Audio and Power) for Use in Electronic and Communication Equipment," Aug. 15, 1945.

of 700 volts (peak) for all windings with (peak) working voltages up to 175 volts, four times the working voltage for windings up to 500 volts, and twice the working voltage plus 1000 volts for higher-voltage windings.

The thickness of interlayer and other sheet insulation necessary for electrical reasons may be calculated from the data in Table 4·6. The values given in the table are safe working-voltage gradients in volts per mil; they may usually be tested at twice the tabulated values and will break down at four or five times the tabulated values.

TABLE 4·6.—WORKING-VOLTAGE GRADIENTS OF INSULATING MATERIALS

Material	Untreated, volts/mil	Varnished, volts/mil	In oil, volts/mil
Kraft paper	40	60	100
Vulcanized fiber	40	60	100
Varnished cambric	100	100	100
Glassine	50	75	100
Formvar	100	100	100
Enamel	20	20	20
Scotch tape	40	40	20
Pure oil	. . .	. . .	125

4·7. Coil Processing.—After a coil is wound and finished it is necessary to treat it in order to drive out whatever moisture it contains and to seal it against the entrance of moisture. A number of processes and materials, which vary considerably in their effectiveness, have been developed for this purpose.

The simplest, cheapest, and least effective of these processes, which is in common use for poor-quality competitive radio transformers, is the wax dip. The coils, with or without the cores in place, are dipped in a container of molten wax and allowed to remain there until all bubbling has ceased, indicating that at least the major portion of the moisture has been driven out, and are then removed and allowed to drain. The process is comparatively ineffective if the temperature of the molten wax is allowed to fall below about 110°C during the early part of the immersion, since the pressure of the steam within the coils will be insufficient to force the moisture out against the hydrostatic head of the molten wax; and the impregnation will be much more thorough if the bath is allowed to cool well below 100°C before removing the coils, since the decreased vapor pressure will allow the wax to be forced into the voids in the coils.

A much more effective method of impregnation is the vacuum process. In this process the coils are placed in an evacuated container, heated to drive out the moisture, and then an impregnating medium, of wax, varnish, or some other material, is admitted to the vacuum chamber and the vacuum released. The atmospheric pressure forces the impregnant

into the voids in the coils; impregnation is usually made more thorough by the use of air pressure after admission of the impregnant. This is a far better process than the simple wax dip, but its effectiveness depends greatly upon the processing schedule. It takes a surprising amount of time to drive out all of the water in a coil, and any impregnation is of little use that leaves more than the slightest trace of moisture. Probably the best check on the drying process is the rate of evolution of moisture, which is most easily determined by the degree of vacuum for a given pumping speed. Near the end of the process, when moisture is coming off more slowly, the rate can be checked by closing the vacuum line and observing the rate of rise of pressure in the chamber. Actual values depend upon the particular installation and to some extent on the character of the charge in the chamber. The manufacturers of processing equipment will furnish schedules of processing, and information can also be secured from the makers of impregnating material.

A number of materials can be used for processing. Cheap transformers often depend upon beeswax, usually mixed with paraffin or rosin. Special "amorphous" waxes of high melting point are considerably better, but the impregnating varnishes especially developed for the purpose are better than any wax, especially for high-temperature operation. Impregnating varnishes vary considerably in their properties, and the recommendations of the manufacturers should be followed with regard to the type used and the processing schedule. Two varnishes, Irvington 100-clear and Harvel 612C, were used by the Radiation Laboratory, and proved excellent for most purposes, the Harvel being somewhat harder and more brittle. A properly impregnated coil should be so solid that it can be cut in half with a band saw and show no voids or air spaces.

Varnish impregnation is satisfactory for units operating up to about 10 kv, but for higher voltages it is preferable to operate the units immersed in oil. All moisture should be driven out under vacuum, but if the oil is clean it is not necessary to use a vacuum better than 29 in. of mercury. One precaution necessary in winding coils intended for oil immersion is to avoid the use of components containing rubber, such as rubber-based adhesive tapes or rubber-insulated coil leads. The oil softens and dissolves the rubber, causing the coil to loosen up and sometimes causing breakdown, and the dissolved rubber contaminates the oil.

High-voltage units can be built for operation without oil immersion by suitable insulation of the high-voltage winding. This is ordinarily done by radially taping or "half-lapping" the coil. Half-lapping consists of taping the coil in a direction perpendicular to the windings, threading each turn through the coil and overlapping the preceding turn by half its width. One half-lap of 5-mil varnished cambric or rayon is good for about 2 kv. The coil should be varnished before half-lapping and after

each two layers. Varnished cambric was originally used by the Laboratory for this purpose, but the more absorbent and flexible acetate-rayon tape referred to above proved so much better that it entirely displaced the cambric.

Transformers intended for operation in air at voltages above 35 kv should depend upon increased spacing for insulation. The high-voltage winding should be supported by suitable insulators at a distance of from 2 to 5 in. from the nearest grounded object such as core or primary This construction also serves to reduce the capacitance of the high-voltage winding to ground, but the inherently high leakage reactance results in poor voltage regulation. Complete oil immersion, with or without increased spacing, is preferable to dry operation of high-voltage transformers.

As a means of eliminating the increased weight of hermetic sealing, especially on airborne equipment, several improved materials for impregnating and coating, which are supposed to be highly resistant to moisture penetration, have been developed. Chief among these are Westinghouse "Fosterite," GE "Permafil," BTL "Flexseal," and Utah Radio Products "Styraseal." These processes all use a thin fluid as an impregnant and the same or a similar fluid loaded with an inert filler as a coating material. The fluids are presumably monomeric plastics, such as meta-styrene, which polymerize to hard tough solids during the curing process. The chief disadvantages of Fosterite, Styraseal, and Permafil is that they severely restrict the choice of materials that may be used in the construction of the transformer.

Although it is possible to build excellent transformers under this restricting condition, it does slow up the manufacturing process and increase the expense. Styraseal may be used as a coating over ordinary varnish-impregnated coils, in which case the restrictions do not apply. Flexseal does not have the material limitations of the others but it is not as tough and it requires that the coil be half-lapped to present a smooth surface on the ends. In order to determine the relative effectiveness of impregnating and sealing materials a test program was inaugurated in July 1945 under the supervision of the Laboratory for Insulation Research of the Massachusetts Institute of Technology. It was found within a few weeks after the program had started that none of the commercial varnishes or other impregnants was good enough to meet Service specifications, and the program was expanded to develop a new impregnant that would be acceptable to the Services. At the termination of operation of the Radiation Laboratory the testing and development programs were still under way, and were not far enough advanced to permit the publication of definite conclusions. It is expected that the work will be continued under Service auspices.

4·8. Shielding.—Transformers and other coils must often be shielded, and this shielding may be either of two types, electrostatic or electromagnetic.

The simpler of the two is electrostatic shielding, which is used to prevent capacitive coupling between two windings of a coil, or between a winding and an external field. Electrostatic shields ordinarily consist of sheets of copper foil or some similar conducting material which are inserted between the two windings to be shielded from each other. It is easy to secure 100 per cent effective electrostatic shielding between two windings by making the foil long enough to permit a lap joint at the ends, the only precaution necessary being to insulate the joint so as to prevent the formation of a short-circuited turn. The shield is usually connected to ground, but sometimes may be connected to other suitable points in the circuit. If a grounded winding is located between the two windings which are to be shielded from each other the shield is not usually necessary. A common example of such an electrostatic shield is the shield that is used between the primary and the high-voltage secondary of most power transformers, which serves as a fairly effective means of preventing any r-f noise that may be present on the supply line from reaching the output via the capacitance between primary and secondary. On units intended for operation at 60 cps it is usually sufficient to ground the shield to the core at one point; for operation at 400 cps it may be necessary to ground the shield at each end of the coil.

Electrostatic shielding against external fields is rarely necessary and is easily accomplished by the use of almost any sort of conducting end bell or can, but electromagnetic shielding is a much more difficult problem. It is usually required to reduce the pickup of hum in the windings from an external magnetic field, but may sometimes be used to reduce the leakage field of a power transformer or choke.

The most effective method of electromagnetic shielding is to completely enclose the transformer in a can of high-permeability alloy such as Mumetal. A single Mumetal can of 10-mil thickness will ordinarily give only about 10 db reduction in pickup, but if several concentric cans are used, alternating between Mumetal and copper, with the copper cans either seamless or well soldered except for the lids, shielding of about 30 db per pair of cans may be attained. It is necessary to provide the can lids with lips so that the joint at the top will be lapped and not a straight crack; fields will sneak in through a crack to a most surprising extent. The Mumetal cans must be annealed in hydrogen after all forming operations are completed, since the high permeability of the material is greatly reduced by coldworking. If the astatic or "humbucking" construction shown in Fig. 4·15 is used in conjunction with threefold composite

Mumetal and copper shields the resulting pickup will be negligible for almost any purpose.

There is a common belief that the use of a heavy cast-iron case will afford a useful degree of shielding for a transformer. This is definitely untrue; measurements on a number of commercial transformers in cast-iron cases showed less than 6 db of shielding, and if the top of the case was left open the reduction was as little as 2 db. Drawn steel cases are slightly better if completely closed except for small holes for the leads, but again the shielding is not enough to be of much use. Hum pickup may sometimes be reduced by careful reorientation of transformers on a chassis, but this expedient is a makeshift at best. The only real remedies are astatic coil construction and the use of adequate high-permeability plus eddy-current shields.

4·9. Mountings, Enclosures, and Terminals.—A great variety of mountings and enclosures has been used for transformers, depending upon the requirements of the individual case. Most of these are intended for chassis mounting, usually flush with the surface by means of flanges, studs, or screws, but there are a number of types, such as the familiar half-shell mounting, which require that a hole be cut in the chassis so that the unit may project through it. Such a mounting may permit a reduction of over-all cabinet volume in some cases, and has the definite advantage that the mounting plane is close to the center of gravity of the unit, but the additional labor involved in cutting out the large hole in the chassis is a serious disadvantage in laboratory construction. Some commercial units are adapted for mounting in any of several positions, which offers a certain amount of freedom in chassis layout.

Enclosures are also of many types, the completely open types in which the coil and part of the core are exposed, the semienclosed forms using end bells, the semisealed potted types, and the truly hermetically sealed units, either potted in compound or oil-immersed. In general the degree of protection of the windings increases with the total weight, although it is by no means true that a heavy transformer is necessarily adequately protected. The principal advantage of the semienclosed unit is the mechanical protection afforded to the windings, usually at the cost of a minor increase in weight, although improved appearance is by no means a disadvantage. Total enclosure in a can filled with potting compound but not hermetically sealed does delay the absorption of moisture by the windings, and affords adequate protection for most ordinary climates. If the potting compound is exposed to air, however, complete protection cannot be guaranteed since all such materials are pervious to some extent, and oxidation, cracking at low temperatures, or flow when hot may expose the windings. The only method of ensuring

complete immunity to unfavorable climatic conditions is true hermetic sealing by solder or some other means that will not deteriorate with age.

Cans.—Transformer cans are usually made from light-gauge sheet steel, although aluminum or some other nonmagnetic material may be used in certain cases where the location of a steel of poor magnetic quality close to the air gap of the core would affect the characteristics of the unit. In many cases the can is made of fairly heavy material so that it can transmit acceleration forces from the core clamps to the external supporting brackets. This is poor practice, especially for oil-filled units, since the concentration of stress at the points of attachment between brackets and can is sufficiently high to produce distortion and eventual failure unless the can is made extremely heavy. Weight will be saved and a stronger unit produced if a light-gauge can is used and an adequate supporting structure provided which is mechanically independent of the can. This is the only satisfactory method of producing a unit to pass the Service shock and vibration tests.

Quantity-production cans may be deep-drawn from seamless sheet. This procedure makes an excellent can that will conform fairly closely to the shape of the core and coil assembly, but it is only practical in cases where the expense of drawing dies is justified. Most small-lot cans are rectangular to permit fabrication in an ordinary sheet-metal shop. Joints may be soft-soldered, brazed, or resistance-welded. Soft soldering gives an oil-tight joint if done with reasonable care, but the solder is inherently weak and subject to failure under vibrational stress; it should never be used as a mechanical connection but only as a sealing medium. If vibrational or shock stresses are negligible, however, a good lapped and soft-soldered joint is satisfactory. Torch brazing or welding gives a strong tight joint but is difficult to accomplish in light-gauge material without excessive warping, and the subsequent cleaning of the joint is a nuisance. Resistance welding gives excellent joints and is cheap, but usually cannot be depended upon for oil-tightness unless the joints are filled with soft solder after spotwelding. The use of tin- or lead-coated steel greatly facilitates making good soft-soldered joints but may cause difficulty in spotwelding.

Potting.—For most low-voltage units the use of potting compound is preferable to the complications of oil filling. There are many such compounds on the market, of varying quality, and the catalogues of the manufacturers should be consulted for details. One compound that was much used by the Radiation Laboratory is Mitchell-Rand 868-EX, which is effective and easy to handle in production. Potting is essentially a "messy" process, however, and if more than a very few transformers are to be potted it will pay to use a regular compound-melting unit with temperature regulation and bottom-pouring spouts. The transformer

assemblies should be preheated to a temperature above the melting point of the compound, if possible, to prevent the formation of a "cold-shut" between the compound and the transformer, which would act as a channel for the admission of moisture. Since the melted compound is extremely viscous a distance of $\frac{3}{16}$ in. should be left on all sides between the assembly and the can, although $\frac{1}{8}$ in. will suffice if necessary. Cooling should not be too rapid since the compound shrinks considerably and its heat conductivity is poor, so that premature solidification of the outside portion may result in the formation of voids next to the coil.

Oil Filling.—The two principal problems entailed by the use of oil filling are the prevention of leaks and the provision for expansion of the oil. Leak prevention is largely a matter of workmanship, although the design of the can should be such as to prevent the transmission of appreciable stresses across soldered joints and to facilitate the flow of solder into the lapped joints. The high thermal expansion coefficient of transformer oil presents a considerable problem with units that must be exposed to a wide range of temperatures. In some cases, such as the small high-voltage units of Fig. 4·17, the flat sides of the can may be allowed to spring sufficiently to take care of the change in volume, but in many cases some special expansion device must be used. This usually takes the form of a metal bellows or "Sylphon," many forms and sizes of which are on the market. Rubber bags have also been tried; such experiments have been conducted at the Radiation Laboratory and by the British at Telecommunications Research Establishment.

The total change in volume of the oil can be reduced by the use of sand or small glass beads to make up part of the volume. This method is satisfactory electrically but the maximum theoretical displacement for spherical particles is only 66.7 per cent and in practice it runs closer to 45 or 50 per cent. The use of sand necessitates a guard to keep it out of the convolutions of the bellows, the additional parts usually take up as much space as was originally saved, and the sand adds a great deal of weight, so that in the long run it is usually better to use plain oil.

Bushings.—One of the principal problems in the development of acceptable hermetically sealed units has been the provision of satisfactory bushings. The first to be used by the Radiation Laboratory were the rubber-sealed types shown in Fig. 4·28. These were satisfactory both mechanically and electrically when first installed but the progressive deterioration of the rubber with age effectively destroyed the sealing after a year or two. Another objection to these bushings was the large number of parts, which increased both cost and assembly time.

A program begun with the T. C. Wheaton Company eventually led to the production of the Wheaton T-1300 line of solder-seal bushings shown in Fig. 4·29. These bushings have a metallic glaze fired directly

onto the glass so that they can be soldered to the can. The T-1302, T-1304, and T-1305 have been used extensively. The T-1301 has been less satisfactory because the hollow rivet holding its lug goes through to the bottom of the glass, giving a very short creepage path inside the can.

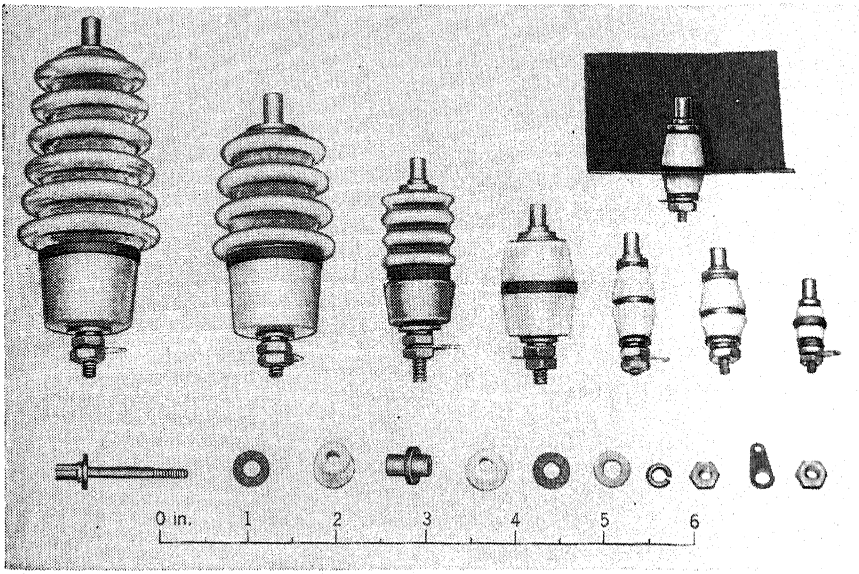


FIG. 4·28.—Rubber-sealed bushings.

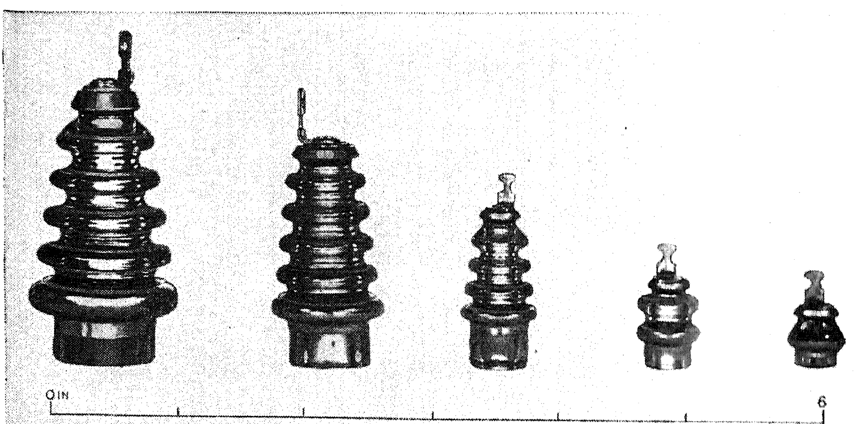


FIG. 4·29.—T. C. Wheaton Co. bushings. (*Left to right:* 1306; 1305; 1304; 1302; 1301.)

Instead of the T-1301 the GE C-12428-A has been much used. This is also a solder-seal bushing, but instead of soldering directly to the glass a metal rim is molded to the bushing and the can is soldered to the rim. Although this bushing also has a stud going clear through, its construction

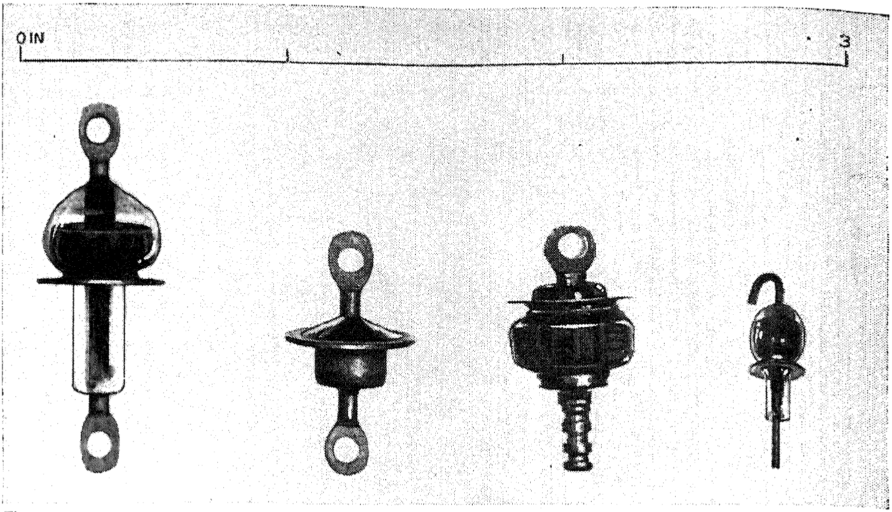


FIG. 4·30.—Metal-to-glass bushings. (*Left to right:* W-103; W-101; C-12428-A; C-13298-A.)

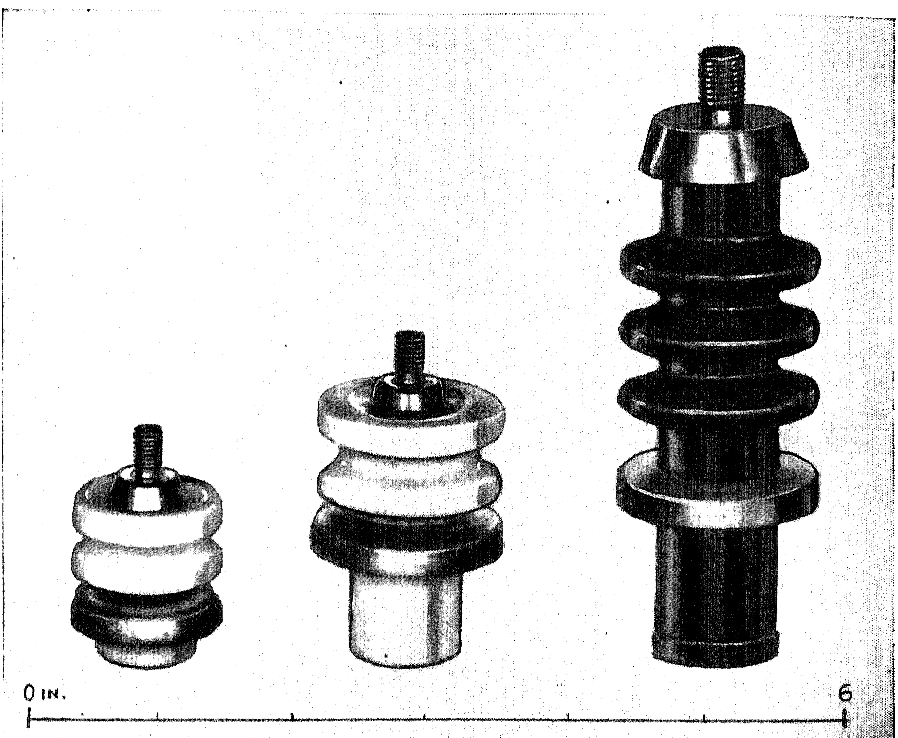


FIG. 4·31.—High-voltage bushings. (*Left to right:* C-12290-A; C-12966-A; C-13330-A.)

is such as to provide a satisfactory internal creepage path. Several other types of small glass bushings which have also been used to some extent are shown in Fig. 4·30.

TABLE 4·7.—BUSHING OPERATING VOLTAGES

Bushing type	Operating voltage at sea level-dry
Large H V	25,000*
Small H V	15,000*
Medium extended	10,000†
Medium	6,000
Small	3,000
Little	1,750
Midget	750
1306	20,000
1305	14,000
1304	10,000
1302	5,000
1301	2,000†
C-12428-A	3,000
W-103	6,000
C-12290-A	12,500
C-12966-A	10,000
C-13330-A	30,000

* With oil inside can.

† With oil or potting compound inside can.

For high-voltage uses porcelain has been used in preference to glass because of its greater mechanical strength. Three high-voltage porcelain bushings developed by Westinghouse are shown in Fig. 4·31. A summary

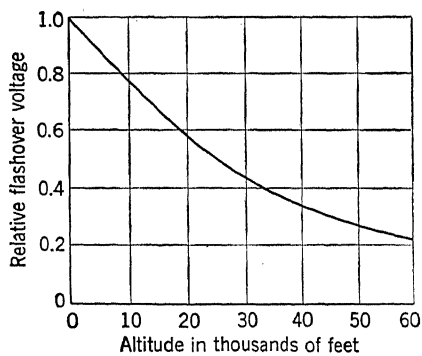


FIG. 4·32.—Derating curve for high-altitude operation.

of the recommended operating voltages for a number of types of bushings is given in Table 4·7, and Fig. 4·32 gives a derating curve for high-altitude operation.

A number of other types of bushings have recently been placed on the market. Besides a wide variety of solder-seal bushings of both glass and

porcelain, several manufacturers are producing bushings in which a central lead or leads are imbedded in a glass bead or slug which is fused into a flanged rim. The metal parts are made of Kovar or Fernico, which has the same expansion coefficient as the special glass over a wide range of temperature. Care should be used if such bushings must withstand extremely low temperatures, however, since some of these special alloys have a low-temperature phase transformation that results in a considerable change in volume with resulting cracking of the glass. Where low temperatures are involved the bushing manufacturer should be notified of the required minimum and a stabilized metal should be used. These bushings are available in a number of forms, including multiple-lead varieties in which a number of leads, each with its own glass bead, are

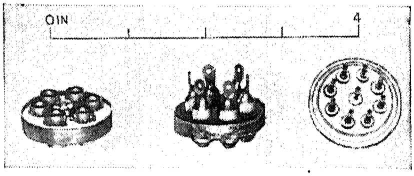


FIG. 4·33.—Multiple-lead bushings. (*Left to right:* T. C. Wheaton; Westinghouse; Sylvania.)

sealed into a multiple-hole header. Three types of multiple bushing are shown in Fig. 4·33.

Another recent bushing construction involves the use of injection-molded lead borate-mica glass (Mycalex, Mykroy, etc.) as the insulating material. It is stronger than either glass or porcelain and has excellent electrical characteristics, but at the present time the price of such bushings is very high. If their excellent qualities lead to sufficient use to bring the price down they should become very popular. Similar bushings have been produced using plastics as the insulating material, but they have not been particularly successful. The molding process is inherently inexpensive and flexible and permits the use of a wide variety of inserts and flanges.

Assembly.—Several methods of soldering bushings to covers were used at the Radiation Laboratory, including soldering iron, torch, induction heating, and infrared heating. The first two tend to concentrate too much heat in one place, stripping the glaze from glass bushings and doing an uneven job. They are useful, however, on the large metal-flanged bushings. Induction heating heats only the metal parts of a bushing directly, tending to expand the flange away from the glass, and also to buckle covers that have a large number of holes. By far the most successful method is infrared heating, which heats all parts evenly and quickly and is uniform and easy to control. An infrared oven built by the Laboratory is shown in Fig. 4·34. It uses a total of twenty-four 350-watt ruby infrared lamps, arranged in six rows of four. A cover with its

bushings in place, each furnished with a small preformed solder ring, is placed on the track and pushed slowly through the oven. A cover 6 in. square with 15 to 30 bushings can be completed in 40 to 50 sec.

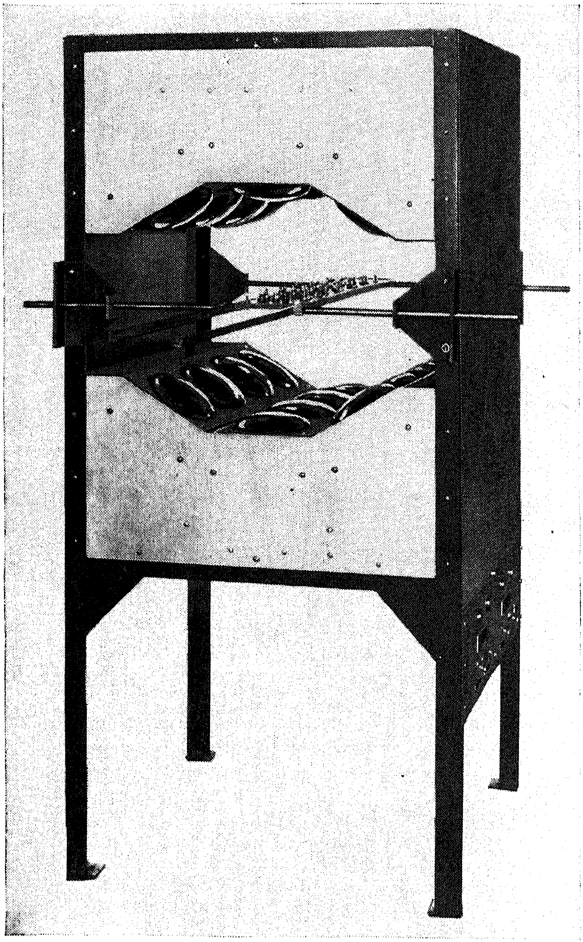


FIG. 4·34.—Infrared soldering oven.

CHAPTER 5

PIEZOELECTRIC DEVICES[1]

BY P. F. BROWN AND S. FRANKEL

QUARTZ-CRYSTAL FREQUENCY STANDARDS

In the field of radar, quartz crystals are used as frequency standards because of their stability and high Q. They are frequently used not in

[1] Much information on the physics of crystals and upon the manufacturing processes used in preparing crystal slabs is contained in the following articles by Bell System authors:

E. J. Armstrong, "X-ray Studies of Surface Layers of Crystals," *Bell System Tech. Jour.*, **25**, 136–155 (January 1946).

W. L. Bond, "The Mathematics of the Physical Properties of Crystals," *ibid.*, **22**, 1–72 (January 1943).

———, "A Mineral Survey for Piezo-electric Materials," *ibid.*, **22**, 145–152 (July 1943).

———, "Methods for Specifying Quartz Crystal Orientation and Their Determination by Optical Means," *ibid.*, **22**, 224–262 (July 1943).

——— and E. J. Armstrong, "Use of X-rays for Determining the Orientation of Quartz Crystals," *ibid.*, **22**, 293–337 (October 1943).

A. R. D'heedine, "Effects of Manufacturing Deviations on Crystal Units for Filters," *ibid.*, **23**, 260–281 (July 1944).

I. E. Fair, "Piezoelectric Crystals in Oscillator Circuits," *ibid.*, **24**, 161–216 (April 1945).

R. M. C. Greenidge, "The Mounting and Fabrication of Plated Quartz Crystal Units," *ibid.*, **23**, 234–259 (July 1944).

C. W. Harrison, "The Measurement of the Performance Index of Quartz Plates," *ibid.*, **24**, 217–252 (April 1945).

F. R. Lack, G. W. Willard, and I. E. Fair, "Some Improvements in Quartz Crystal Circuit Elements," *ibid.*, **13**, 453–463 (July 1934).

W. P. Mason, "Quartz Crystal Applications," *ibid.*, **22**, 178–223 (July 1943).

——— and R. A. Sykes, "Low Frequency Quartz-crystal Cuts Having Low Temperature Coefficients," *Proc. IRE*, **32**, 208–215 (April 1944).

H. J. McSkimin, "Theoretical Analyses of Modes of Vibration for Isotropic Rectangular Plates Having All Surfaces Free," *Bell System Tech. Jour.*, **23**, 151–177 (April 1944).

R. A. Sykes, "Modes of Motion in Quartz Crystals, the Effects of Coupling and Methods of Design," *ibid.*, **23**, 52–96 (January 1944).

———, "Principles of Mounting Quartz Plates," *ibid.*, **23**, 178–189 (April 1944).

G. W. Willard, "Raw Quartz, Its Imperfections and Inspection (Chap. IV)," *ibid.*, **22**, 338–361 (October 1943).

———, "Use of the Etch Technique for Determining Orientation and Twinning in Quartz Crystals," *ibid.*, **23**, 11–51 (January 1944).

Most of the information in these articles and much besides is to be found in R. A. Heising, *Quartz Crystals for Electric Circuits*, Van Nostrand, New York, 1946.

the CRT display equipment itself but in associated driver units, calibrators, or test equipment.

Since the crystals used in radar equipment need not satisfy as rigid Q and stability requirements and since they are required in quantities small compared to those used in communication equipment, the procurement problem has not been serious for radar-equipment manufacturers. Moreover, because of the lower Q required and because they were usually used in the frequency range of 50 to 200 kc/sec (20- to 5-μsec markers), manufacturing facilities and techniques were already available (as was not the case in the vhf communication field).

The frequency stability necessary is derived from the over-all requirements of the more precise CRT displays and special test equipment. Precise CRT displays do not usually require better than ± 0.05 per cent stability and crystals in special test equipment may vary by as much as ± 0.025 per cent. Thus a 100-kc/sec calibrator with a variation of ± 0.05 per cent would furnish 10-μsec markers on a time base with an accuracy of ± 0.005 μsec. In a radar set the 0.05 per cent specification implies a range accuracy of 2.0 yd at 4000 yd or of 15 yd, at 30,000 yd, if there are no other errors in the system.

5·1. Use of Quartz Crystals in Radar.—The principal factors to be considered when using a crystal for radar purposes are temperature coefficient; initial accuracy; susceptibility to damage by shock, vibration, and humidity; and the electrical circuits.

Temperature Coefficient.—This is the most important of these factors. For equipment used by the Armed Forces the required ambient temperature range is $-40°$ to $+80°$C. In laboratory test equipment the temperature range is more likely to be $+15°$ to $+70°$C. The crystals usually used are of the bar type, which have a frequency-temperature curve flat near 25°C and falling off for extreme negative or positive temperatures, thus making the coefficient positive at lower temperatures and negative at higher temperatures. One such type (Valpey RL) has a coefficient of $+2.0$ and $-3.0 \times 10^{-6}/°$C for temperatures above and below the normal. Another type (Bliley FM-6) has coefficients of $+1.6$ and $-1.4 \times 10^{-6}/°$C from $+20°$C to $-40°$ and $+60°$C respectively. In the extreme case of a 100-kc/sec crystal with a coefficient of $5.0 \times 10^{-6}/°$C and zero error at 25°C, the shift to $+70°$C would give a frequency shift of 22.5 cps or of 0.022 per cent. Since the more recent crystals have a coefficient of about $1 \times 10^{-6}/°$C, this factor is not critical for radar applications.

Initial Accuracy.—Initial accuracy is easily obtained. For example, the final calibration of a production run of 82-kc/sec crystals will show that they are all within 25 cps and that 80 per cent will be within 15 cps. The equivalent accuracies are 0.03 and 0.018 per cent respectively.

Shock, Vibration, and Humidity.—The susceptibility of the crystal to damage by shock, vibration, and humidity has forced a new method of packaging. The crystal types used for the comparatively low frequencies mentioned above are the bar, which vibrates lengthwise, and the wafer, which vibrates in shear. Since there is a node in the center in each case, the crystal elements may be tightly clamped at the center. For one type (Valpey RL), which is a bar 33 mm long, the clamp may be placed at least ± 2 mm from the lengthwise center and adjusted to any degree of tightness. Shock and vibration tests have shown that the center-clamping method is satisfactory. In fact, with shocks of 110 g the pins in the socket break before the quartz bar gives way. A few broken crystals were obtained and examination proved that the bar is more likely to break in half at the clamping point than to slip out of the holder.

Humidity conditions may be severe for military equipment but present no serious problem for the crystals of the types described, since they have always been tightly packaged to keep out dirt and to prevent atmospheric corrosion of the silver plating. The package is usually metal, such as a metal tube shell, the only problem being to seal the insulated output leads tightly. Manufacturers still have two problems, adequate tropicalization and the selection of an insulating material that retains its low dielectric loss after use and exposure.

Electrical Circuits.—The effect of the electrical circuit on the crystal is usually small. Tests in which a triode oscillator and a crystal holder with two pins were used showed that reversing the holder in its socket changed the frequency of an 82-kc/sec crystal by 2 to 7 cps. This shift may be eliminated by grounding the metal case. Moving the 2-in. grid lead in the same oscillator caused a frequency shift of 6 cps. In another instance, where a triode oscillator had a pulse transformer in its cathode circuit, the frequency could be pulled by the feedback of signals through the transformer, but putting the transformer in the plate circuit corrected this trouble. In those instruments in which the power output of the oscillator is varied by changing the tuning of an r-f transformer in the plate circuit, it was found advisable to use a pentode as the oscillator tube. Changing the self-bias on the Radiation Laboratory type triode oscillator will change the frequency 2 to 3 cps. Changing the tuning of a pentode oscillator with the tank circuit in the cathode may change the frequency by as much as 25 cps. Crystal-oscillator circuits in general are discussed in Vol. 19, Sec. 8·5.

5·2. Special Quartz Cuts.—For some applications special quartz cuts have been selected or developed.

Pulsed crystal oscillators are used when it is necessary to keep the oscillations always in phase with random triggers or pulses. This is done

by shock-exciting the crystal, letting it run for the required number of cycles, and then completely stopping it until the next shock excitation. The standard Radiation Laboratory 82-kc/sec crystal (18° X-cut and length-to-width ratio of 0.35) vibrates in two modes and when shock-excited has an amplitude modulation caused by beats between the 82- and 95.6-kc/sec modes. As a result of this, Valpey's Type RL was developed to operate in a single mode. It is a 0° X-cut with a length-to-width ratio of 0.147. This ratio was selected in order to make the frequency of the coupled-flexure mode well removed from 82 kc/sec.

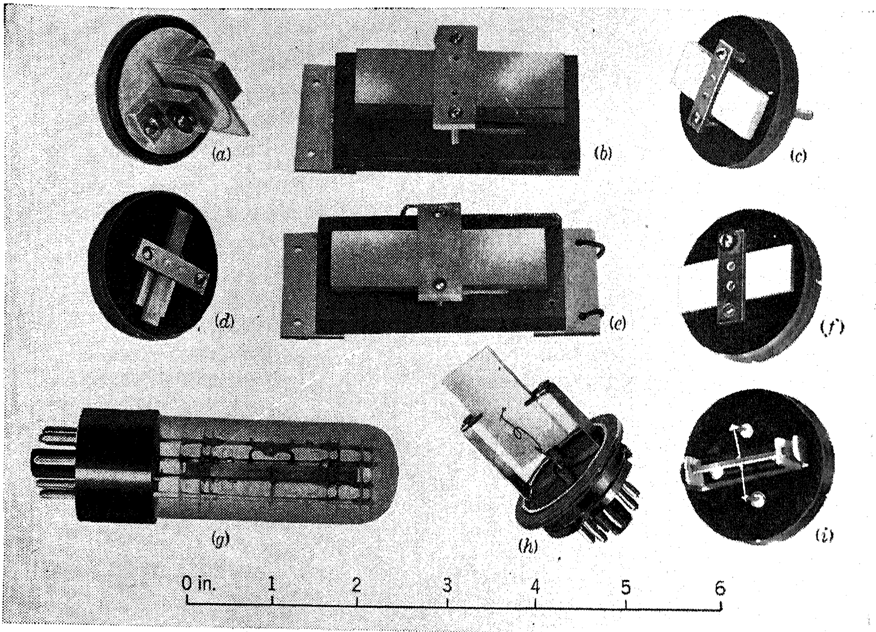


FIG. 5·1.—A collection of crystal types showing the quartz bars and type of mounting.

Manufacturer and Type	Frequency, kc/sec	Manufacturer and Type	Frequency, kc/sec
(a) Bliley, Type FM6	81.95	(f) Valpey, Type XLST	80.86
(b) Valpey, Type XL	49.16	(g) BTL D171117	2
(c) Valpey, Type XL and XLS	81.94	(h) GE Type 32C401	81.95
(d) Valpey, Type RL	81.94	(i) Valpey, Type XLR	93.11
(e) Valpey, Type XLS	40.93		

During 1943 to 1944 the shortage of quartz caused a redesign of the low-frequency cuts to save quartz. For example, Valpey modified their Type XLS into the Type XLST, and the latter into Type XLR, as is shown by Fig. 5·1 (*c*, *f*, and *i*). A similar modification is also shown by Fig. 5·1 (*b* and *e*). In addition to saving quartz, the new cuts proved to be more active.

The very-low-frequency range for a quartz crystal (i.e., 2 to 4 kc/sec)

TABLE 5·1.—QUARTZ-CRYSTAL FREQUENCY STANDARDS USED BY THE RADIATION LABORATORY

Mfg.	Type	Shown in Fig. no.	Cut	Freq., kc/sec	Temp. coeff. per 1°C	Temp. range, °C	Mounting
Valpey	XL and XLS	5·1*b*, *c*, *e*; 5·2 *b*, *c*	18° X-cut	40.43 80.86 81.94 93.11 164.0	−2 to −5 $\times 10^{-6}$	−20 to +80	On nodal line by 2-point clamp
Valyey	XLST	5·1*f*	18° X-cut thickness reduced and new length-to-width ratio	80.86 81.94	−2 to −3	....	Same as XL
Valpey	XLV	....	CT	163.93	<1	....	In center by 3 points
Valpey	CBC	....	AT	819.4	1	....	Air gap
Valpey	XLR	5·2*c*	5° X-cut	80.86 81.94 93.11	1 to 2	....	Leads soldered to crystal faces
Valpey	XLT	5·2*e*	5° X-cut	80.86	1 to 2	....	Soldered leads, mounted in ½″ × 1½″ cylinder
Bliley	FM6	5·1*a*, 5·2*a*	DT	70 to 110	2	−40 to +60	In center by 3 points
GE	32C401 G43	5·1*h*, 5·2*d*	Twisted X-cut	81.96	3	....	Soldered leads, in metal tube housing
WE	D171117	5·1*g*, 5·2*f*	....	2.000		....	Soldered leads, in sealed glass tube

* Frequency will remain within ±0.04 per cent of 2000 cps for all temperatures between −40° and +70°C.

is covered by a development of the Bell Telephone Laboratories and the Western Electric Company. Figure 5·1 (*g*) shows a 2-kc/sec crystal of this type. It is a duplex unit with two electrodes on one side and a common one on the other. This split electrode is necessary to get the proper mode of vibration.

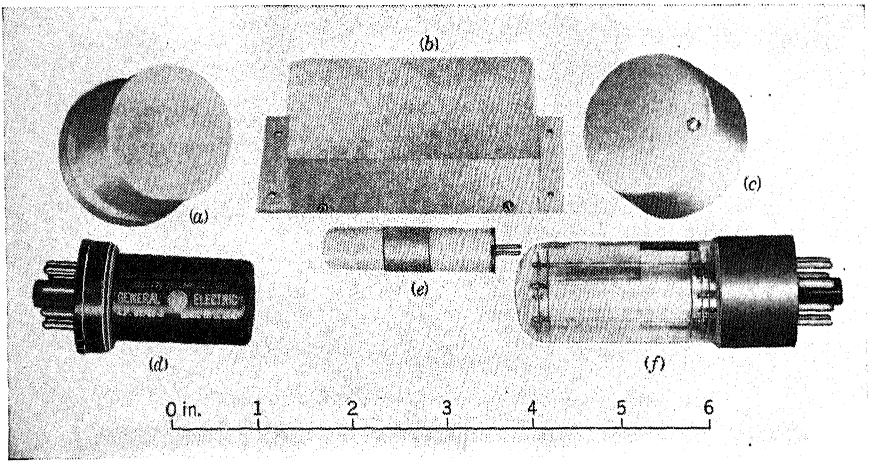


FIG. 5·2.—A collection of crystal types showing external appearances.

Manufacturer and Type	Frequency, kc/sec	Manufacturer and Type	Frequency, kc/sec
(*a*) Bliley, Type FM6	70 to 200	(*d*) GE, Type 32C	80 to 165
(*b*) Valpey, Type XL and XLS	40 to 50	(*e*) Valpey, Type XLT (miniature)	80 to 200
(*c*) Valpey, Type XLS and XLR	80 to 200	(*f*) BTL, Type D171117	2

SUPERSONIC CRYSTAL TRANSDUCERS

The transducer described in this section was developed for underwater use in a supersonic system designed to simulate radar echoes. In this system a piezoelectric crystal, submerged in a tank of water, is excited with a high-power (approximately 1 kw) pulse of 15-Mc/sec energy. The compressional waves produced in the liquid are shaped by suitable reflectors and spread out over the surface of a reflecting map located at the bottom of the tank. Waves reflected from the map impinge on the quartz crystal and the voltage produced by the piezoelectric action is amplified, detected, and displayed on the usual radar indicator.

The requirements for this transducer were

1. That it should not introduce appreciable power losses other than those representing power radiating out into the water.
2. That there must be no spurious reflections within the crystal cartridge (mount).

3. That the crystal should be easily replaceable and easily assembled into its cartridge.
4. That the cartridge must not leak during long periods of immersion in water.
5. That the transducer must be designed to withstand the application of powers of 3 watts (average) at approximately 2000 volts.
6. That the electrical characteristics of the mounted crystal must be such that electrical circuits of maximum power efficiency can be designed.

The operating frequency of a supersonic echo-simulating system is determined by the range requirements. The absorption in water of supersonic energy in the 10- to 30-Mc/sec band has been shown experimentally to increase as the square of the frequency (at 15 Mc/sec at 20°C the absorption is 67 db/m). Thus in a supersonic system the range is determined largely by the logarithmic absorption, although the usual $1/r^4$ attenuation is still present.

The crystal cartridge to be described has been used with 10-, 15-, 25-, and 30-Mc/sec quartz crystals, but there is no reason to believe that this range could not be extended to 40 or 50 Mc/sec.

The crystal cartridge was designed in an attempt to obtain maximum efficiency and therefore the crystal was backed with air rather than with solids or liquids as the latter have an acoustic impedance of approximately that of quartz. The fact that the crystal is backed with air is advantageous as only a small amount of energy is radiated into the air to become available for undesired multiple reflections within the cartridge. In addition the high absorption of 15-Mc/sec supersonic energy in air militates against the possibility of appreciable fractions of this power returning to reexcite the crystal.

The crystal cartridge was developed for a crash program and by no means represents the ultimate in design.

5·3. The Piezoelectric Crystal.—The specifications for the standard 15-Mc/sec crystals require that the plated but unmounted crystal resonate to a frequency of 15.00 ± 0.15 Mc/sec. The resonant frequency is determined in manufacture by measuring the frequency of an oscillator that employs the crystal as the frequency-determining element. The grid current of the oscillator is used as an indication of "activity." Crystals that do not meet the standard oscillator-crystal grid-current specifications, however, are acceptable in supersonic applications where the crystal is heavily damped. The resonant frequency of the crystal mounted in the cartridge and damped by the action of the water drops to 14.75 ± 0.15 Mc/sec. The resonant frequency of the mounted crystal immersed in a liquid is defined as the frequency at which the conductance

of the crystal is a maximum. The conductance may be readily measured with the General Radio 821-A Twin-T Impedance-measuring Circuit.

The circular crystal is cut from quartz so that the crystallographic x-axis is perpendicular to the faces of the crystal to within 1° as determined by X-ray measurement. No tests have been performed to determine how great an angle may be tolerated. After the two plane surfaces of the crystal are ground to approximate thickness they are etched for at least 100 kc/sec to the desired thickness. A gold plating is sputtered on and is baked for at least one hour at 500°C. Gold is used rather than a less noble metal in order to minimize the possibility of corrosion of the plating by protracted immersion in the water of the echo tank.

5·4. The Crystal Cartridge. *Mechanical Characteristics.*—A drawing of the type 7B crystal cartridge is given in Fig. 5·3. The body of the

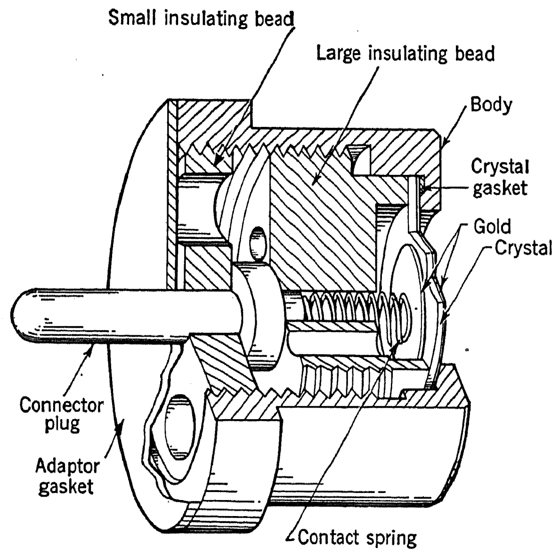


FIG. 5·3.—Supersonic crystal cartridge.

cartridge is made of brass. Brass has been chosen because it is easily machined, and can stand the deleterious effects of continued underwater use. Stainless steel, aluminum, and plastic bodies have been used, but show no advantages over brass. The crystal is kept in place with a large threaded insulating bead that screws down into the cartridge body and forces the crystal against the ledge of the front face of the body. A thin rubber gasket is placed between the crystal and the ledge so that the pressure of the large insulating bead will provide a watertight seal.

Leakage of water through the crystal-ledge interface to the back of the crystal has three harmful effects:

1. The small spacing between the crystal plating and the cartridge body and the conductivity of tap water combine to provide a low-resistance shunt across the crystal.
2. Water in place of air behind the crystal results in an increase in crystal resistance R_s.
3. Half the power delivered to the crystal will be dissipated in the water behind the crystal.

These factors not only add lossy elements to the crystal but also change its impedance and hence detune the matching networks that deliver power to it.

One end of a fine silver contact spring touches lightly on the gold plating of the crystal. The other end is soft-soldered to the connector plug that leads the 15-Mc/sec voltage to the crystal. Another small insulating bead holds the connector plug in place. Holes are provided in both beads to allow insertion of a tool to facilitate assembly. To make the crystal cartridge watertight at the connector-plug end, melted paraffin is usually poured through these holes into the space between the beads. To further reduce the possibility of leakage to the upper bead, a rubber gasket may be employed which fits over the connector plug. The space between the large insulating bead and the crystal is normally filled with air but may be filled with suitable liquids for the purpose of acoustically damping the crystal.

Certain problems in transducer design have arisen that are not met by the transducer described. When high intermediate-frequency voltages are applied to the crystal, the contact between the spring and gold plating often open-circuits. This is due to a "burning" of the gold plating at the point of contact. The cause of this burnout has not been determined but it may be due to arcing between the spring and plating when the crystal contracts. The frequency of burnouts has been greatly reduced by shaping the front end of the spring as shown in Fig. 15·3 to obtain the maximum area of contact between spring and plating. The original type of spring made contact at only one point.

The use of the thin rubber gasket to render the crystal-ledge interface watertight requires careful assembly and, in general, this scheme has not been wholly satisfactory.

One of the most serious drawbacks of the transducer is the presence of the phenomenon of "ringing." When excited by a high-powered pulse, the crystal appears to vibrate after the pulse for a period sometimes as great as 150 μsec. This ringing is not directly observable on a

synchroscope, but if a high-gain amplifier is connected across the crystal (as must be done in a supersonic echo-simulating system) it appears as a block of saturated signals. The ringing time increases as the power to the crystal is increased. These spurious signals are objectionable for they mask return signals at short ranges. No adequate solution to this problem has been found. It is believed that the ringing cannot be accounted for by the natural decrement of the crystal.

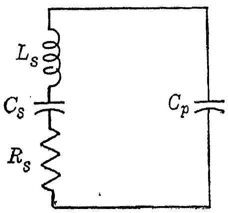


FIG. 5·4.—Equivalent circuit of piezoelectric quartz crystal. C_p = capacitance between both faces of crystal; C_s = equivalent electrical capacitance; L_s = equivalent electrical inductance; R_s = "radiation resistance" of crystal.

Electrical Characteristics.—The electrical characteristics of the crystal were obtained for the crystal mounted in the cartridge of Fig. 5·3. In general the Q of a crystal in air is high. However, the Q of a crystal is appreciably lower when one face of the crystal radiates directly into a liquid medium such as water, whose acoustic impedance is of the order of magnitude of that of the crystal.

An equivalent electrical circuit of the crystal in the cartridge of Fig. 5·3 is given in Fig. 5·4. Here C_p is the capacitance between the plated areas of the crystal plus the capacitance between the "high" side of the crystal (plating, contact spring, and connector plug) and the cartridge itself; L_s and C_s are respectively the equivalent inductance and equivalent capacitance of the crystal and are related to its resonant frequency, ω_0, by the relation $\omega_0^2 L_s C_s = 1$. For piezoelectric crystals the ratio of the capacitance between the plates of the crystal to the equivalent capacitance, C_s, is constant. This ratio, represented by the constant α, is approximately 140 for quartz. The "radiation resistance" of the crystal R_s is a function of the surrounding medium. For the crystal in the mount of Fig. 5·3, radiating into water, R_s = 4700 ohms, C_p = 20 $\mu\mu$f, and C_s = 0.14

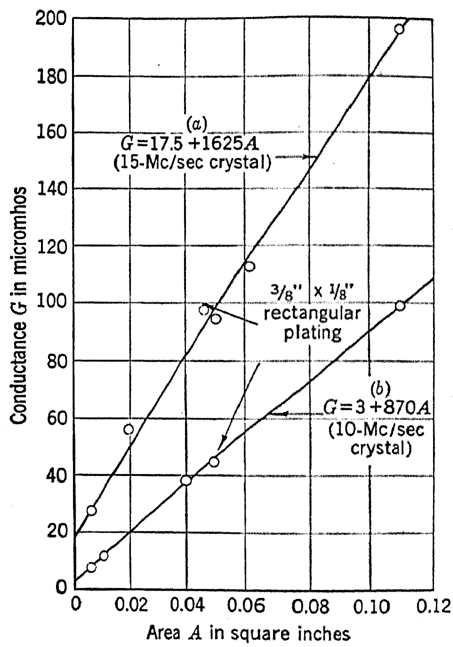


FIG. 5·5.—Conductance of quartz crystal vs. back-plating area. All front platings ½-in. diameter. All back platings circular except as indicated.

$\mu\mu$f.[1] For these values it is apparent that the Q of the crystal, defined as $1/\omega_0 C_s R_s$, is approximately equal to 16. The "front" face of the crystal (the face radiating out into the water) is fully plated and therefore grounds to the ledge of the cartridge. The "back" plating must be of smaller diameter so that it is sufficiently removed from the

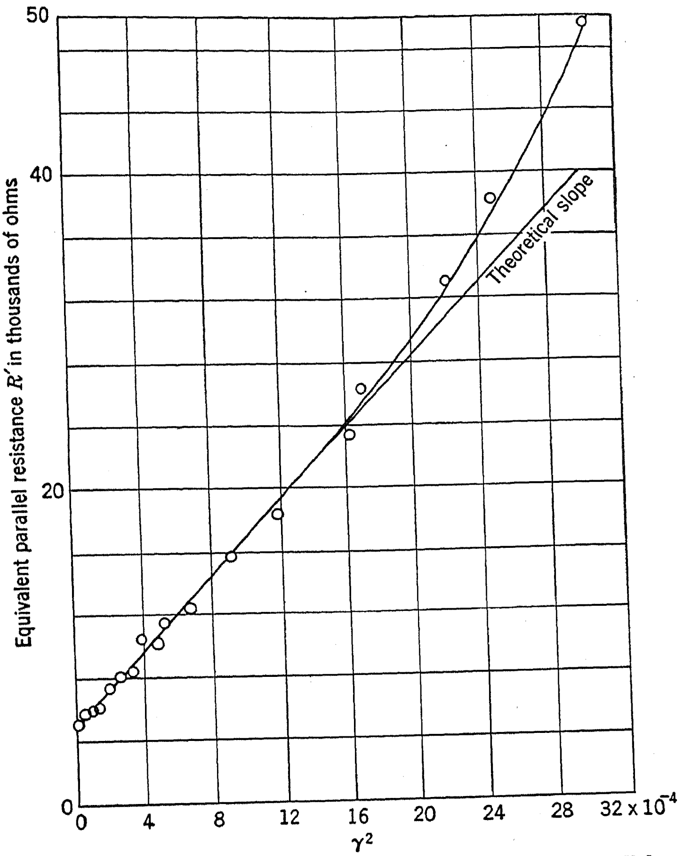


FIG. 5·6.—Validity of equivalent circuit of Fig. 5·4. Equivalent parallel resistance R' [from Eqs. (1) and (2)] is plotted as a function of γ^2. Theoretical slope is R_sQ_s where R_s = 4.7k and Q_s = 16.

side of the cartridge body to prevent arc-over. The radiation resistance of the crystal is essentially a function of the smallest plated area, in this case the back plating. Figure 5·5 shows the relation between conductance and back-plating area for 10- and 15- Mc/sec crystals in the cartridge of Fig. 5·3. These curves do not cross the origin but show a finite conductance when extrapolated to zero backplate area. This is

[1] R_s and C_s are functions of the back-plating area; the quoted values are for a 15-Mc/sec crystal with a $\frac{3}{8}$-in. circular back plating.

believed to be due to the edge effect resulting from the use of a large constant-diameter front plate. As would be expected this effect is smaller for the thinner 15-Mc/sec crystal than for the 10-Mc/sec crystal.

The effective parallel resistance of the equivalent circuit of Fig. 5·4 can be shown to be given by

$$R' = R_s(1 + Q_s^2\gamma^2), \tag{1}$$

$$\gamma = \left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right). \tag{2}$$

Thus the validity of this equivalent circuit may be determined by plotting the experimentally determined values of R' against γ^2. A representative plot is given in Fig. 5·6. If the equivalent circuit is valid, the slope of this curve should be constant and equal to $R_sQ_s^2$. It appears that the value $Q_s = 16$ is constant in a 2.5-Mc/sec band about the center frequency of 14.75 Mc/sec. At frequencies remote from the center frequency the effective Q_s increases and the equivalent circuit becomes invalid.

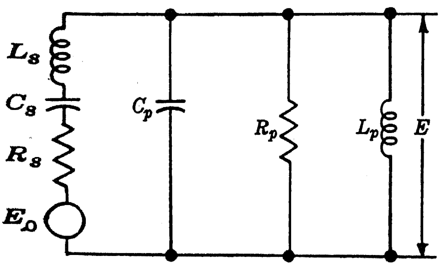


FIG. 5·7.—Equivalent circuit of crystal and tuning network.

In applications in which the bandwidth of the crystal and associated networks is of importance, as it is in a supersonic echo-simulating system, the crystal capacitance C_p is usually tuned to resonance at the crystal frequency. The parallel-tuned circuit that results from this procedure is usually damped with a resistor. Figure 5·7 shows the equivalent circuit of crystal and tuning network for a received signal, the resistor being represented by R_p. If E_0 represents a small voltage induced in the crystal by an incident supersonic wave, the bandwidth of the system is given by a plot of Eq. (3) as a function of γ.

$$\left(\frac{E}{E_0}\right)^2 = \frac{1}{\left(1 + \frac{\alpha}{Q_pQ_s} - \alpha\gamma^2\right)^2 + \left(\alpha\gamma\,\frac{Q_p + Q_s}{Q_pQ_s}\right)^2} \tag{3}$$

A plot of this expression for $\alpha = 140$ for various values of Q_p is given in Fig. 5·8.

It can be shown that the bandwidth of this system may be increased by reducing the Q of the crystal. This may be done by substituting various liquids for air in the space behind the crystal in the cartridge. For example the Q drops to 6.9 with castor-oil or mineral-oil backing and

to 4.2 with methylene iodide backing. Although acoustically damping the crystal in this manner does produce systems of wider bandwidth, it results in a sacrifice of some of the power that would normally radiate into the water. It is possible, however, to increase the bandwidth without loss of power by interposing between the crystal and the medium a quarter-wavelength layer of material of acoustic impedance, $\rho_x C_x$, such that

$$Z_x = \rho_x C_x = \sqrt{(\rho C)_{\text{quartz}} \cdot (\rho C)_{\text{medium}}}. \tag{4}$$

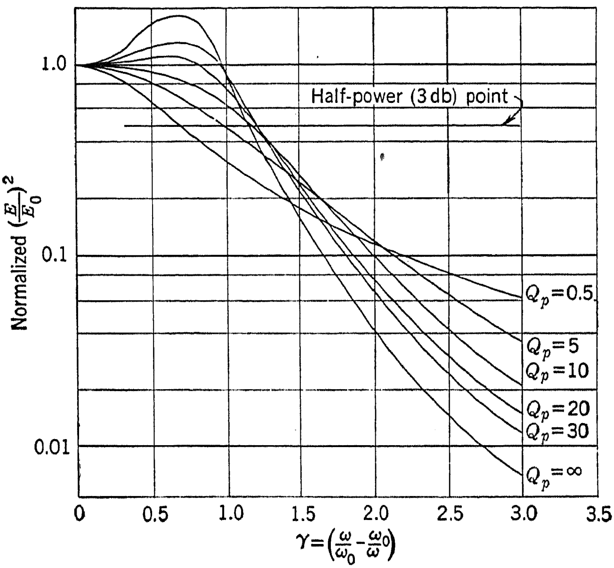


FIG. 5·8.—Frequency response of crystal in circuit of Fig. 5·7, where $Q_s = 15$ and $\alpha = 140$.

Successful work along these lines has been carried out at the Telecommunications Research Establishment in Great Britain.

It is also possible that the bandwidth of the crystal might be increased by proper design of the crystal itself. The properties of wedge-shaped crystals have not been investigated.

Compensating circuits for the crystal may be designed in an effort to increase the bandwidth but these usually result in a serious decrease of gain. One type of compensating circuit is shown in Fig. 5·9.

When the crystal is employed with an intermediate-frequency amplifier it is possible to compensate for the narrow band of the crystal by proper design of the amplifier pass band. This method is somewhat similar to the method of Fig. 5·9 except that the final series-tuned circuit is placed after one or more stages of amplification. In this way the compensation is carried out well above noise level and no serious decrease

of gain need be tolerated. Figure 5·10 shows the pass band of such an amplifier operating at 10 Mc/sec. The frequency response of an assumed crystal and input circuit having a Q of 11.3 was approximated in design

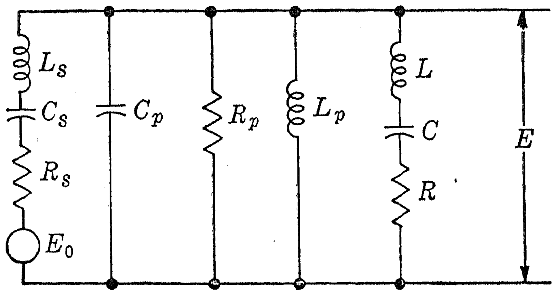


FIG. 5·9.—Crystal compensating circuit.

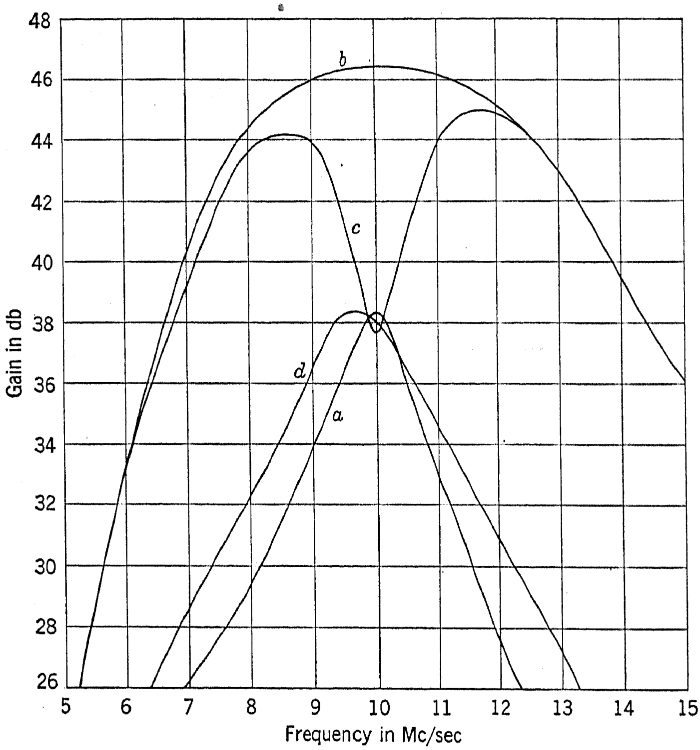


FIG. 5·10.—Bandpass curves of compensating amplifier. Curve a, pass band of simulated crystal and tuning network. Curve b, pass band of uncompensated amplifier. Curve c, pass band of compensated amplifier. Curve d, pass band of over-all system.

by a simple series-resonant circuit. The pass band of this circuit is given in Curve a. Curve b shows the pass band of the uncompensated amplifier alone; Curve c, that of the compensated amplifier; and Curve d,

the over-all pass band of the system. Comparison of Curves d and a indicates an improvement in 3-db bandwidth from 1.3 to 2.1 Mc/sec and there is no reason to believe that compensation greater than this cannot be achieved.

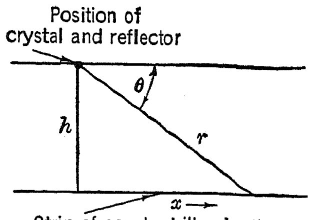


FIG. 5·11.—Geometry of reflector derivation.

5·5. The Reflector.—Experiments indicate that the diffraction of sound waves emanating from the crystal cartridge follow the theoretical predictions for diffraction by a circular aperture.

A reflector designed to produce constant illumination along a line parallel to the face of the crystal can be calculated. If it is assumed that the diffraction of a $\frac{3}{8}$-in. aperture (approximately 65 wavelengths at 10 Mc/sec) is negligible, that the waves from the crystal are essentially plane, and that the aperture of the crystal is small compared

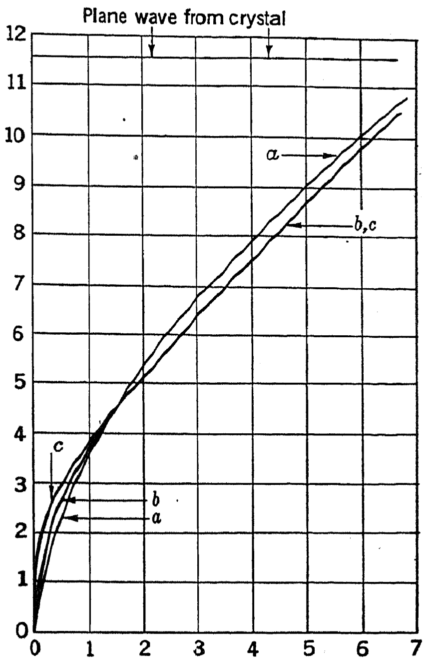


FIG. 5·12.—Curves providing constant illumination. Curve a, trial-and-error curve. Curve b, theoretical curve neglecting absorption in medium. Curve c, theoretical curve including absorption in water at 10 Mc/sec.

with the strip to be illuminated, then the required distribution for constant illumination [$P(\theta)$ = constant] is given by

$$P(\theta) = P_0 h^2 \csc^2 \theta e^{-2\alpha h \csc \theta}. \tag{5}$$

The quantities involved in this equation are indicated in Fig. 5·11. This formula is based on $1/r^4$ attenuation and on the logarithmic absorption of the supersonic waves given by

$$P = P_0 e^{-2\alpha r}, \tag{6}$$

where α is the absorption coefficient.

From the conservation of energy, the following equation is obtained:

$$P(x)\, dx = P(\theta)\, d\theta. \tag{7}$$

The energy incident on the reflector is constant if the radiations from the crystal are plane waves.

If there is no absorption ($\alpha = 0$), Eq. (7) may be integrated and yields as the required surface

$$y = \ln \frac{1 + \sqrt{1 + x^2}}{x^2} - \sqrt{1 + x^2}. \tag{8}$$

If however $\alpha \neq 0$, Eq. (7) must be graphically integrated for any one value of αh. Both types of calculated curves are plotted in Fig. 5·12. They are identical within the precision of the plot for those sections of the reflector that throw energy out to large ranges. Both curves are calculated for a 50-cm coverage when $h = 3.5$ cm. Curve b is the theoretical curve in which absorption is neglected. Curve c is calculated including the absorption at 10 Mc/sec in water, for which $\alpha = 3.45$. Curve a is that of a hand-tooled reflector that was made by trial-and-error methods and was not entirely satisfactory.

CHAPTER 6

ELECTROMAGNETIC DELAY LINES

BY H. E. KALLMANN

Since pulsed radar is based upon measurement of time intervals,[1] one of its most frequently recurring problems is that of delaying pulses or blocks of signals for accurately known times. Basically there are at least two solutions to this problem: one involves recording a signal in some kind of storage device and reproducing it at a known time later; the other involves feeding the signal into one end of a "long" transmission line and taking it out at the other end after an interval equal to the time of transmission along the line. The storage technique, which involves the use of image-storing tubes whose operation is similar to that of the iconoscope of RCA, is outside the field of this volume but is discussed in Vol. 19, Chap. 21. The transmission-line technique led to the development of the two classes of devices which form the subjects of this chapter and Chap. 7. The choice of the method to be used in a particular case depends principally upon the magnitude of the delay required: the electromagnetic delay lines are most useful for delays up to a few microseconds, the acoustic delay lines up to milliseconds, and the storage-tube techniques up to seconds. The applications of the delay lines and the details of their associated equipment and circuits will be found in Vol. 19, and Vol. 20, Chap. 13; this chapter and Chap. 7 describe a number of delay lines of both types and give a full discussion of methods of design.

Steep-fronted signals are attenuated and distorted in delay lines, as in any other network, because of transmission losses and phase distortion in the lines and mismatch at their ends. The degree of fidelity required differs widely for different applications.

The main design parameters of an electromagnetic delay line are its impedance

$$Z = \sqrt{\frac{L}{C}} \qquad \text{ohms, henrys, farads,} \tag{1}$$

and its time delay

[1] "Thou knowst we work by wit, and not by witchcraft: and wit depends on dilatory time." Othello II, 3.

$$T = \sqrt{LC} \qquad \text{seconds, henrys, farads.} \tag{2}$$

For a given impedance and time delay the inductance is determined by

$$L = TZ, \tag{3}$$

and the capacitance by

$$C = \frac{T}{Z}. \tag{4}$$

Delay lines are designed to provide the required inductance and capacitance in a small space without undue signal distortion.

The most conservative delay line is a length l of coaxial cable. Its delay, regardless of its impedance, is

$$T = \tfrac{1}{3} \cdot 10^{-10} \cdot l\sqrt{k} \qquad \text{seconds, centimeters,} \tag{5}$$

where k is the dielectric constant of the space between the conductors. Thus a polyethylene cable with k equal to 2.25 delays signals by 1 μsec per 200-m length.

Electromagnetic delay lines may be grouped into two classes: The distributed-parameter type, formerly called "condensed cable,"[1] and the lumped-parameter type, derived from low-pass filter networks.

6·1. Distributed-parameter Delay Lines. *Characteristics.*—Delay lines of the distributed-parameter type are practicable for the impedance range from 200 to over 3000 ohms. In their simplest form they are derived from a coaxial cable or a parallel line by changing one conductor into a long thin coil; because of the resulting increase in inductance both the delay and the impedance increase. Close spacing of the two conductors increases the capacitance; this also increases the delay but reduces the impedance.

The inductance of a long cylindrical coil is

$$L_0 = \frac{10^{-9}\pi^2 d^2}{w} \qquad \text{henrys per centimeter,} \tag{6}$$

where w is the pitch and d the average diameter, both measured in centimeters. The inductance so computed applies exactly at low frequencies only. At higher frequencies, currents in different turns along a delay line, although still magnetically linked, are less and less in phase with each other and add less and less to each other's magnetic field. The separation of two turns having a given phase difference decreases in proportion to the frequency; their mutual inductance thus drops and later reverses. This effect manifests itself as a steady drop in the effective inductance L

[1] H. E. Kallmann, "Transversal Filter," *Proc. I.R.E.*, **28**, No. 7, 302–310, (July 1940).

of the winding, as is shown in Fig. 6·1.[1] The ordinate is L/L_0, that is, the effective inductance L compared with the low-frequency inductance L_0. The abscissa is proportional to frequency. The drop in effective inductance L at a given frequency f will increase as the phase difference between any two points increases—that is in proportion to the delay T per unit length of line; and the drop will also increase as the coupling between two given turns becomes stronger, that is, proportion-

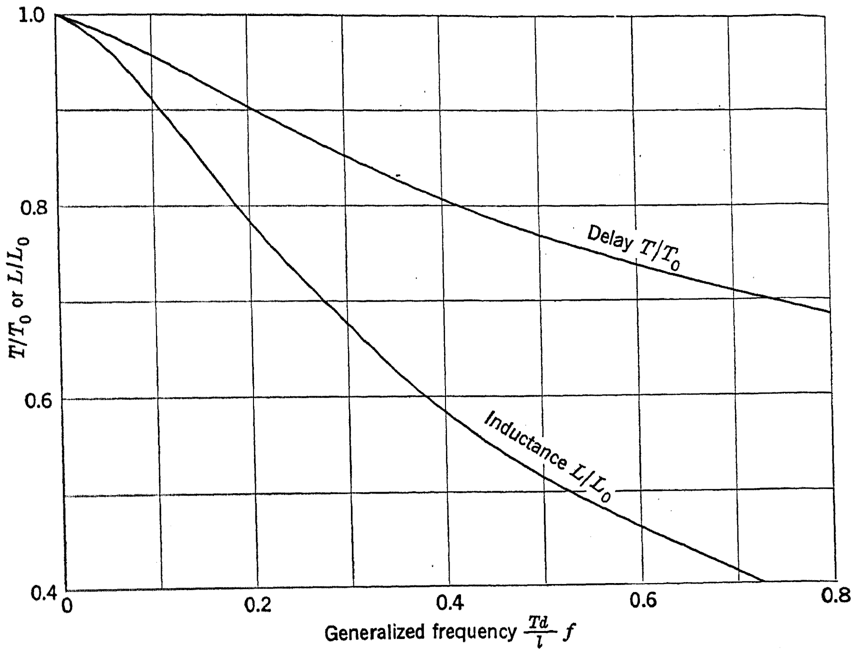


FIG. 6·1.—Effective inductance and time delay vs. frequency.

ally to the diameter d of the turn and inversely proportionally to the separation l. Thus the generalized frequency scale of Fig. 6·1 is presented in units of $\frac{Td}{l}f$.

Because the distributed capacitance C of a delay line varies widely with the geometry of the design and the dielectric properties of the spacer, it is not easily computed. The capacitance between conductors does not vary significantly with frequency.

Because inductance decreases as frequency increases the delay T of a simple delay line is a function of frequency, decreasing steadily as plotted in Fig. 6·1. This decrease in time delay manifests itself as phase distor-

[1] J. P. Blewett, R. V. Langmuir, R. B. Nelson, J. H. Rubel, "Delay Lines," GE Report, May 31, 1943; also J. P. Blewett and J. H. Rubel, "Video Delay Lines," *Proc. I.R.E.*, **35**, 1580–1584 (December 1947.)

tion, the phases of the high-frequency components in a signal being advanced relative to the phase of the low-frequency components. Phase distortion severely affects the shape of pulses, but it can be held within acceptable limits either by conservative design, choice of a low coefficient Td/l, or by the equalizing means[1] discussed in Sec. 6·2.

Signals are also distorted by the attenuation in the line. Equal attenuation of all signal frequencies is not considered distortion; it is harmful only in applications such as pulse-forming circuits where the absolute rather than the relative steepness of the echo front is important. Because of increased attenuation of the higher-frequency components, pulses that were originally square are rounded as they are in a system with too narrow a pass band.

Attenuation in delay lines is due to resistance of the conductor and to dielectric losses between conductors. The attenuation A_R due to the resistance R of the conductor is

$$A_R = 4.35 \frac{R}{Z} \qquad \text{db,} \tag{7}$$

where R is the total series resistance of the line in ohms. The resistance R rises with frequency because of skin effect; this rise starts, for example, near 2 Mc/sec in a coil of AWG No. 40 copper wire and soon reaches a slope of $R \approx \sqrt{f}$. However, the amplitude distortion due to skin effect plays only a minor role in delay lines used at present. With the materials now available for wire insulation, dielectric losses are more important by far.

The dielectric losses arise: (1) in the space between the two conductors; (2) between turns of a coiled conductor. The loss between the conductors can be held down somewhat by insertion of low-loss dielectrics as spacers between conductors; the losses between the turns of a coiled conductor can be reduced by spacing the turns, with a corresponding increase in line length, or by reducing the wire thickness. Formex insulation (a polyvinyl plastic now widely used), although better than others, is still unsatisfactory for frequencies above 2 Mc/sec. The relative contributions of skin effect and dielectric loss in AWG No. 40 Formex HF wire (0.0031-in. copper, OD 0.0036 in.) may be gauged from Fig. 6·2. The broken line shows the attenuation obtained with a 0.003-in. wire crudely hand-coated with a low-loss plastic.

Attenuation of high-frequency components is also caused by mismatch at the ends of a terminated line. The impedance of a line does not stay exactly constant over its whole useful frequency range, but because

[1] H. E. Kallmann, "Equalized Delay Lines," *Proc. I.R.E.*, **34**, No. 9, 646–657 (September 1946).

of the drop in effective inductance and the unavoidable load capacitance it usually changes slightly at the higher frequencies. At lower frequencies, for which the delay line is accurately matched, all power is delivered to the load. At the higher frequencies, at which the line is mismatched, a

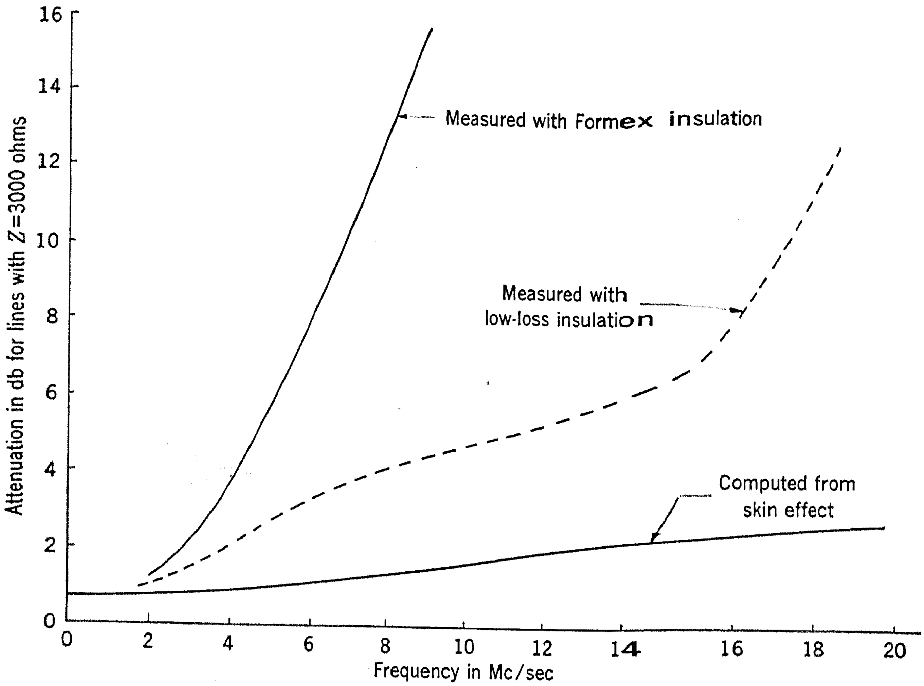


FIG. 6·2.—Relative contributions of skin effect and dielectric loss to attenuation.

fraction of the power is reflected at the termination, partly reflected again at the input terminal, and then appears at the output terminal as a short pip after each transition, delayed by twice the delay time of the line. (See Fig. 6·3.)

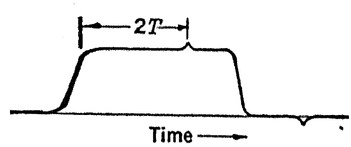


FIG. 6·3.—Effect of mismatch at high frequencies.

Another appreciable mismatch occurs within the line just before the end. In this region, the inductance per unit length of the line changes because each turn is coupled to fewer and fewer other turns. Flaring of the ends or the insertion of conical pieces of iron-dust core may be used as a mean of compensation for manufactured lines. Another means of compensation is the simple expedient of cutting the line into small pieces. Thus the line may be wound in many equal sections, each of which produces an end echo; the sections, however, are so short that the echoes form a ripple of invisibly high frequency. If, for example, each section has a delay of 0.025 μsec, the echo ripple would

correspond to an oscillation of 20 Mc/sec and its harmonics. None of these frequencies would pass through a line with a cutoff of, for example, 16-Mc/sec. Such lines are used in oscilloscopes for signal delay at high impedance levels.

Faults such as short circuits or uneven distribution of capacitance in a delay line may show up as anomalous humps in the time-delay characteristic. They are certain to show conspicuously in the transient response as echoes from the defective place. Touching a point of the coiled conductor will also give an echo pip because of the locally increased ground capacitance; and by moving one's finger along the coil, this pip can be made to move along the transient response and to ride on the fault echo when the faulty place is touched.

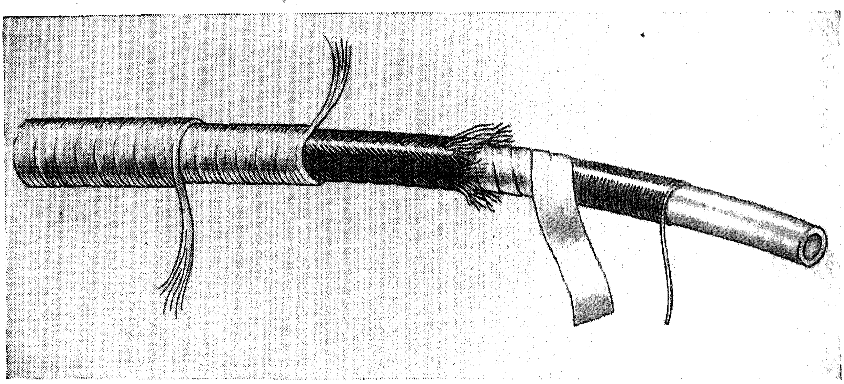


FIG. 6·4.—Uniform delay line, General Electric Company.

Delay lines, wound either continuously or in sections, can be made with much higher impedance than can be properly matched. Satisfactory models were made with impedances as high as 4000 ohms.

A lower limit to the impedance attainable is set by the operating voltage, the dielectric constant of the insulator, and the space available since it is necessary to attach more and more distributed ground capacitance to less and less inductance. Unless special dielectrics, multiple wires, or tape are used, the lowest practicable impedance is approximately 200 ohms.

Typical Delay Lines with Distributed Parameters.—A delay line manufactured by the General Electric Company is widely used. Its inner conductor is a long thin coil, its outer one a metal braid surrounding the inner one so closely that it must be braided from insulated wires to avoid excessive eddy-current losses. The manufacturing specification of an early model[1] is:

[1] J. H. Rubel, H. E. Stevens, R. E. Troell, "Design of Delay Lines," GE Report, Oct. 25, 1943; see also references cited on p. 193.

Core: $\frac{3}{16}$-in.-diameter tubing of Saran, a moderately flexible plastic

Winding: AWG No. 40 Copper (0.0031-in. diameter) Formex HF insulation (OD 0.0036 in.) close-wound, 109 turns per centimeter; inductance 20 μh/cm

Insulator: $\frac{3}{8}$- by 0.0015-in. cellulose acetobutyrate tape, single wrap, 50 per cent overlap

Outer conductor: braid of 24 by 8 strands AWG No. 36 (0.005 in.) Formex-insulated copper wire; pitch, 1.9 in; capacitance, 16.5 $\mu\mu$f/cm

Jacket: double cotton wrap (special lines have polyvinyl jacket).

Its electrical characteristics are: impedance Z, 1100 ohms; delay T_0, 1 μsec in 55 cm; voltage rating, 5000 volts d-c. The temperature coefficient of the delay in such lines is +0.12 per cent per degree between −60° and +100°C. The construction of this line is shown in Fig. 6·4. The line is so flexible that it can be bent around a 5-in. diameter. All strands of the braid are grounded at one end. The time-delay characteristic of such lines corresponds closely to the computed curve of Fig. 6·1, dropping 5 per cent in the range from 0 to 10 Mc/sec. The attenuation per microsecond was found to rise from 1.5 to 2 db at very low frequencies to 2 to 3 db at 2 Mc/sec and to 4 to 6 db at 4 Mc/sec. The distortion of a 1-μsec pulse is illustrated in Fig. 6·5, where the shape of the pulse at the input terminal and after 1-, 3-, and 5-μsec delays is shown.

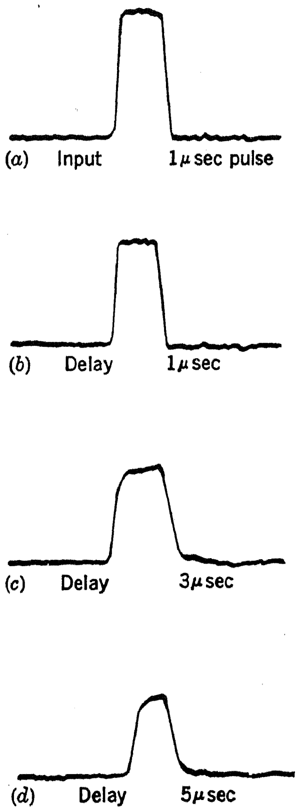


FIG. 6·5.—Distortion of 1-μsec pulse by line of Fig. 6·4.

A somewhat similar simple line was manufactured by the Federal Telephone and Radio Corporation for a special application which required that 0.25-μsec pulses of 25 kv be delayed with less distortion than could be noticed on the best available oscilloscopes. These requirements were met by a line with conservative parameters designed to the following specifications:

Core: polyethylene 0.380 in. in diameter

Winding: AWG No. 23 copper (0.0226 in.) Formex-insulated, close-wound to 15 turns per centimeter

Dielectric: solid polyethylene ($k = 2.25$) extruded to 0.680-in. diameter

Outer conductor: single-braid plain AWG No. 35 copper wire
Jacket: polyvinyl to 0.875-in. over-all diameter.

This line, shown in Fig. 6·6, closely resembles the RG-65/U high-impedance cable (Sec. 1·12) but has a relatively much larger coil diameter ($a/d < \sqrt{e}$) which serves to increase the delay.

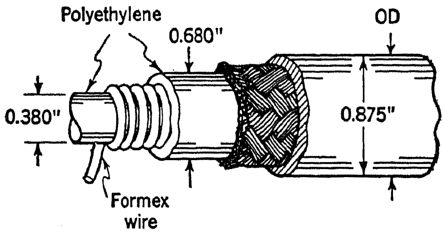


FIG. 6·6.—Uniform delay line, Federal Telephone and Radio Corporation.

The delay line of Fig. 6·6 has an impedance of 830 ± 10 ohms and a delay of 1 μsec in 500 cm. When a 0.5 μsec pulse whose front rises from 0.1 to 0.9 of its total rise in less than 0.03 μsec is transmitted through a length of this line which gives a delay of 0.5 μsec, the output pulse is attenuated 0.6 db and shows a slight rounding of its corners, but it still rises from 0.1 to 0.9 in less than 0.03 μsec.

Another line that avoids distortion by a conservative choice of parameters is an experimental variable delay line, of which one conductor is again a long thin coil, and the other a grounded strip of metal foil placed between the winding and its core. Its design specification is as follows:

Core: 0.30-in.-diameter tubing of Saran
Grounded conductor: soft copper foil 0.090 in. by 0.001 in.
Insulator: one layer of kraft paper 0.001 in. boiled in ceresin wax
Coil: AWG No. 30 copper Formex-insulated, close-wound with 36 turns per centimeter.

The line, which is 25 in. long, is bent into a circle of 9 in. diameter and furnished with a contact arm, similar to that of a wire-wound potentiometer. The line impedance is 1,000 ohms. Its total delay is 0.44 μsec, calibrated in equal steps of 0.01 μsec and reliable at all points to 0.002 μsec for frequencies up to at least 20 Mc/sec. For use as a variable delay line its far end is terminated in the characteristic impedance and the signal taken off by a contact sliding on a bared path on the coil. The load at this point should be of high impedance, but the calibration is remarkably insensitive to a load at the contact even if it is comparable to the line impedance.

The impedance of delay lines is increased if both conductors are solenoidal in form. Such lines consist of two windings on a slim insulating core, continuously wound on top of each other with opposite winding sense. Such lines are called "balanced delay lines;" however, the signal

traveling along them does not remain balanced with respect to ground because the diameters of the two windings, and therefore their inductances per unit length, are not exactly equal. This imperfect balance does not matter in such applications as pulse-forming circuits where the far end of the line is either short-circuited or open.

Balanced lines, close-wound in two layers of AWG No. 37 Formex wire on $\frac{3}{16}$-in.-diameter core, were used experimentally in pulse-forming and pulse-coincidence circuits; their impedance was 620 ohms.

Simple delay lines are adequate for the formation and delay of trigger pulses and, with moderate fidelity, for signal delay. Unless obscured by

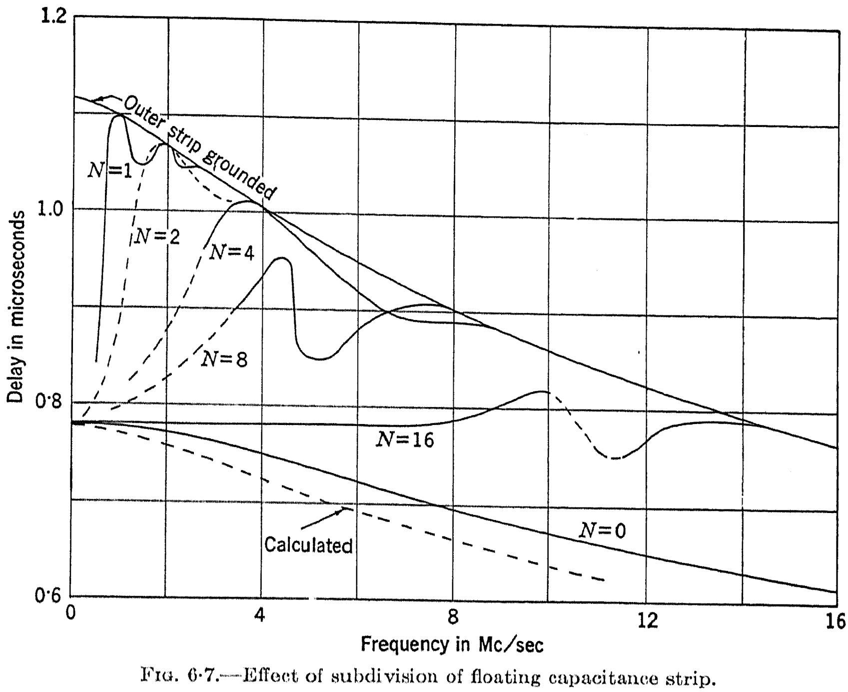


FIG. 6·7.—Effect of subdivision of floating capacitance strip.

very bad attenuation, asymmetric distortion of pulses, as shown in Fig. 6·5*d*, will be noticeable. For more stringent requirements, such as signal delay in oscilloscopes, equalization of the phase distortion is necessary. This equalization has been achieved by the addition of phase-equalizing networks,[1] but, even for modest improvements, the size and the complexity of the networks may exceed that of the delay line itself.

6·2. Equalizing the Time-delay Characteristic. *Methods.*—A simple means of equalizing the time-delay characteristic is the addition of a

[1] D. F. Weekes, "A Video Delay Line," RL Report No. 61-20, Apr. 26, 1943.

bridge capacitance that effectively increases with higher frequencies. This method of equalization may be understood from the observations plotted in Fig. 6·7. A continuous coil of AWG. No. 28 enameled wire was close-wound on an insulator of $\frac{3}{4}$-in. diameter and 16-in. length over a paper-insulated strip of copper foil 0.001 by 0.160 by 15 in. Its time delay, plotted as $N = 0$ (Fig. 6·7), dropped steadily from 0.78 μsec at low frequencies to 0.616 μsec at 16 Mc/sec. This rate is somewhat less rapid than that calculated from Fig. 6·1. Another strip of copper foil was then mounted along the outside of the coil and held in place with tape. Connecting it to the inner copper strip and to ground just doubled the ground capacitance; the initial time delay was thus increased by $\sqrt{2}$ to 1.1 μsec, and the time delay dropped steadily to 0.764 μsec at 16 Mc/sec. When one of the two strips was disconnected from ground, but left in place, a different type of curve was observed. The new curve started at $T_0 = 0.78$ μsec. This effect was expected since at very low frequencies there is no phase difference between any two turns of a low-loss line, and therefore no alternating current flows by way of the floating strip from any turn to another turn in any bridge circuit formed by the capacitances. However, at very high frequencies, when $f \gg 1/T$, the time-delay response will be the same as if the floating strip were grounded because at those frequencies, the equal couplings to turns at all phases cancel each other in their effect upon the potential of the strip. Similar cancellations also take place at certain lower frequencies, whenever $f = 1/T$, $2/T$, etc. These may be observed near $f = 0.9$ Mc/sec and $f = 1.8$ Mc/sec in the curve for $N = 1$.

From the curve for $N = 2$ in Fig. 6·7, it is seen that the delay at very low and very high frequencies is unaffected if the floating copper strip is cut into two equal pieces, each extending over one half of the line. The curve for $N = 2$ resembles the curve for $N = 1$ except that the peaks at lower frequencies occur at twice the former frequency, when $f = 2/T$, $4/T$ etc. If the floating copper strip is divided into three or four equal lengths, the peaks occur at proportionally higher frequencies. Continued subdivision of the floating copper strip, however, leads to a different type of curve. The delay at very low frequencies is still that of the unpatched line; it rises steadily with increasing frequency to a peak just below the frequency

$$f_p = \frac{N}{2T}, \tag{8}$$

where T is the total delay at that frequency and N the number of equal floating patches along the line. The delay drops sharply at f_p, then recovers to follow the curve of a line with all patches grounded. This type of response is observed on the model with 8 and with 16 equal floating patches. The delay response for these higher numbers of patches has

its peak at a frequency for which each patch extends over about one-half wavelength on the line. The phenomenon is different from that observed at $N = 4$, when the patches were one whole wavelength at the first peak. The change-over is rather sudden, as plotted in Fig. 6·8.

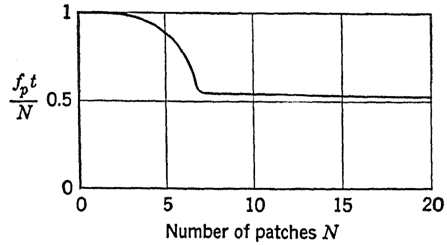


FIG. 6·8.—Wavelength per patch at peak.

The smooth rise to the peak of the time-delay characteristic is utilized for the equalization of delay lines. The desired isochronism—or some other desired time-delay characteristic—is adjusted by the choice of two parameters, the length and width of each patch; periodical change of the size of the patches may offer a third means of adjustment. The number of patches is always so large that Eq. (8) applies. The characteristic is then generally smooth over a frequency range to at least $0.8f_p$. Thus the lowest number of patches required for the equalization up to $0.8f_p$ is

$$N = 2Tf_p. \tag{8a}$$

There is no harm in choosing a larger number of patches, provided that they can be made proportionally wider. The width of the patches and the thickness and dielectric constant of the insulation between them and the coiled conductor serve to control the amount of bridge capacitance. At higher frequencies the delay is increased in proportion to these capacitances, and isochronism may therefore be adjusted by the width or thickness of insulation of the patches, as illustrated in Fig. 6·9 for a line with T_0 equal to 0.90 μsec. The response of this line before equalization dropped steadily to 0.82 μsec at 16 Mc/sec. An application of 24 patches, each 0.10 in. wide and 1 in. long, resulted in overcompensation of the drop, but over too narrow a frequency range, the frequency of the peak, f_p, being 10.8 Mc/sec. Another curve shows the result after each patch was cut in two, resulting in 48 patches, 0.10 in. by 0.50 in. The peak moved outside the observed range, presumably to 25 Mc/sec, and the equalization was nearly correct, rising to 0.93 μsec at 16 Mc/sec. A slight reduction of patch width then adjusted the delay characteristic to just-equal delays of 0.90 μsec at zero and at 16 Mc/sec, with a drop of less than 1 per cent in between. If necessary, this curvature can be further equalized by

adding another row of about 14 slim patches which contribute a slight lift with a peak frequency near 8 Mc/sec.

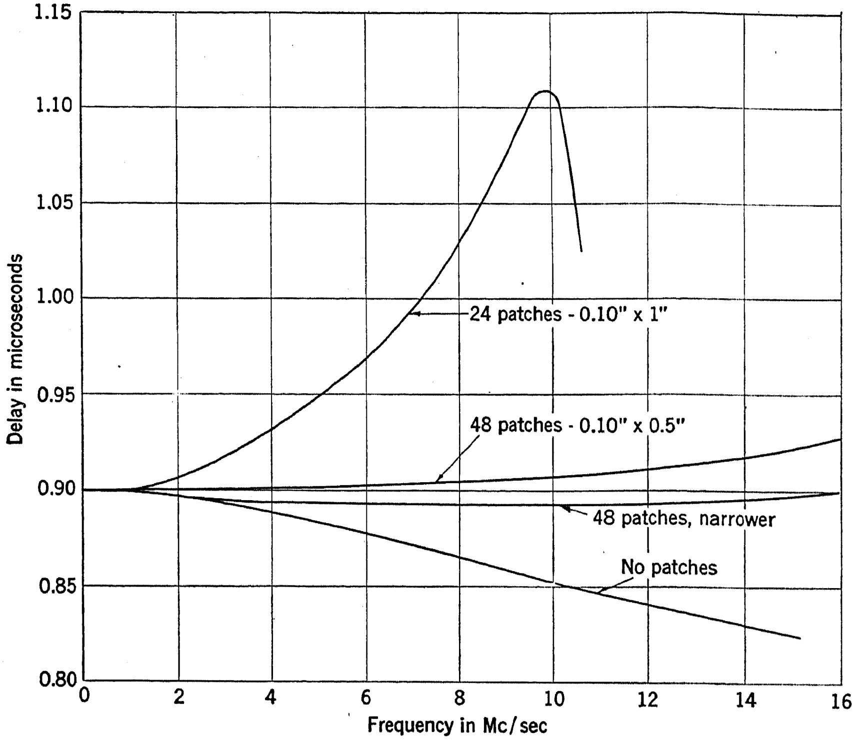


FIG. 6·9.—Effect of size and subdivision of patches.

In these models the delay characteristics, even before patching, did not drop as much as was calculated. This fact can be attributed to the natural coil capacitance C_L, which may be found from the inductance of the coil and from the frequency at which it resonates without external capacitance. It is best estimated from the following relation:

$$C_L \approx d, \qquad \text{micromicrofarads, inches.} \tag{9}$$

Accordingly, the effects of natural bridge capacitance in a delay line are found to increase with the diameter of the line. Most of the bridge capacitance is on the outside of the long slim coils. If, therefore, a substantial part of the surface of the coil is covered by grounded conductors, such as the metal braid used on the GE lines, all but neighboring turns are effectively screened from each other and equalization due to natural coil capacitance is suppressed (see Fig. 6·10).

For a given coil diameter, the less ground capacitance per turn is required, the higher the desired impedance of the line. The natural coil

capacitance, however, is not reduced. Thus, with increasing line impedance, narrower and, finally, no equalizing patches are required.

Another means of influencing the delay characteristic of a line is to divide its winding into sections. This method results in loss of induc-

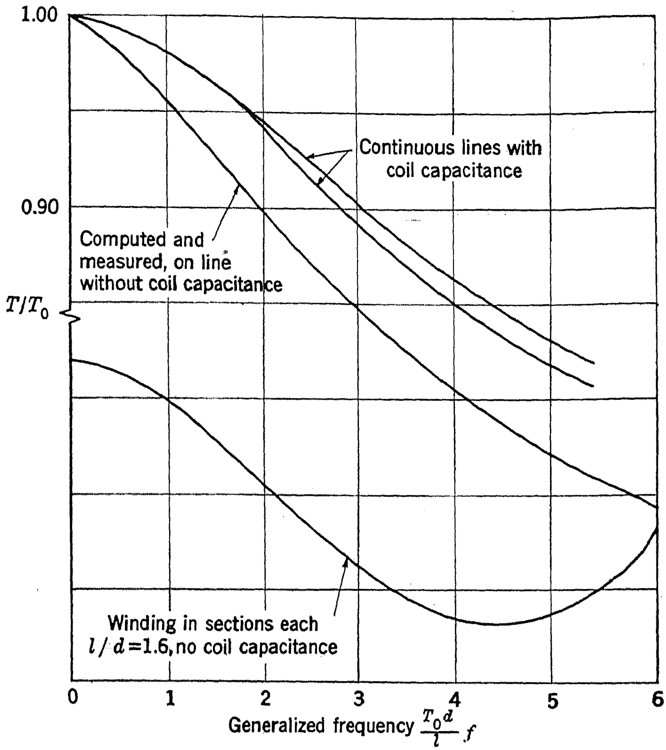


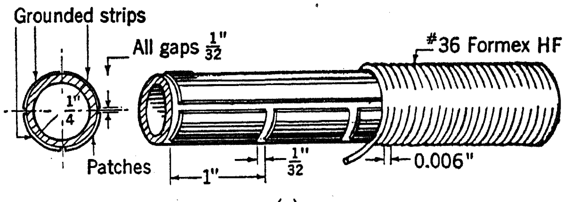
FIG. 6·10.—Effect of natural coil capacitance and of subdividing coil.

tance which causes less delay per length, and consequently less drop in the delay characteristic. It also results in a conspicuous cutoff frequency at which the delay rises to a peak as shown by the lower curve in Fig. 6·10, representing a coil wound in spaced sections with natural coil capacitance suppressed by a cover of braid. Delay lines wound in sections and with floating patches have certain special merits and several examples will be discussed.

Typical Equalized Delay Lines.—In the following examples the delay equalization is driven well beyond the beginning of excessive attenuation. These designs should be justified as soon as low-loss insulated wires become commercially available.

The construction of a continuously wound delay line designed for a moderate frequency range is shown in Fig. 6·11. The delay is 1 μsec for about 10 in.; the impedance, 400 ohms. An insulating core of $\frac{1}{4}$-in.

diameter is covered with a conducting layer, by copper plating or by cementing on (with self-curing rubber) thin soft copper foil, which is cut into four full-length strips separated by gaps about $\frac{1}{32}$ in. wide. Three of these strips are grounded and the fourth is divided into a row of floating patches, each $\frac{31}{32}$ in. long, spaced $\frac{1}{32}$ in. apart.[1] The complete core



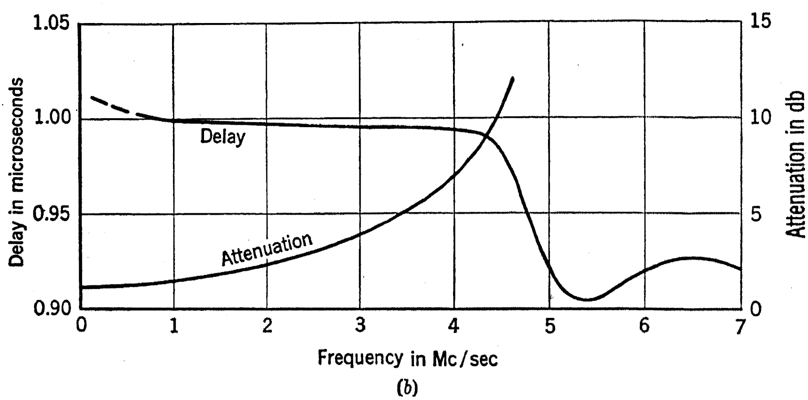


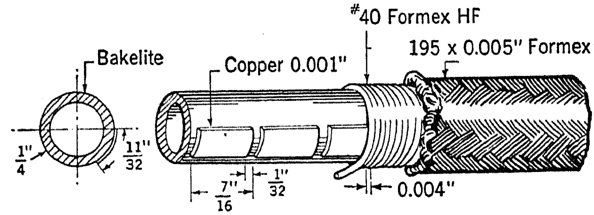
FIG. 6·11 (a and b).—Continuously wound delay line with floating patches and grounded strips.

is given a thin coating of low-loss dielectric and then wound with No. 36 Formex HF wire. The resulting time-delay characteristic is thus equalized to better than one per cent at frequencies up to $f_p = 4.5$ Mc/sec (Fig. 6·11b). The transient response is symmetrical, its shape being due entirely to attenuation. Losses rise to 10 db/μsec before any phase distortion sets in (Fig. 6·11b). The upturn of the delay characteristic at the lowest frequencies, if genuine, is harmless, corresponding to a phase shift well below one degree. Delay lines of this construction are manufactured by the Raytheon Manufacturing Company as type M-10178; they have an impedance of 390 ohms and a delay of 8 μsec, and are fabricated in 14 pieces sealed in a metal case of approximately 5 by 5 by 10 in.

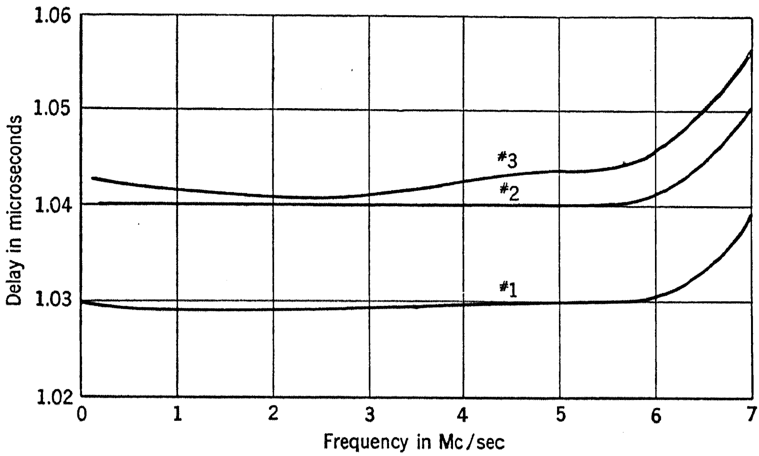
Another design of a continuously wound line, shown in Fig. 6·12, is a

[1] Such cores, made of Pyrex glass rod with grounded and floating strips of burnt-on silver, are commercially available from Corning Glass Works.

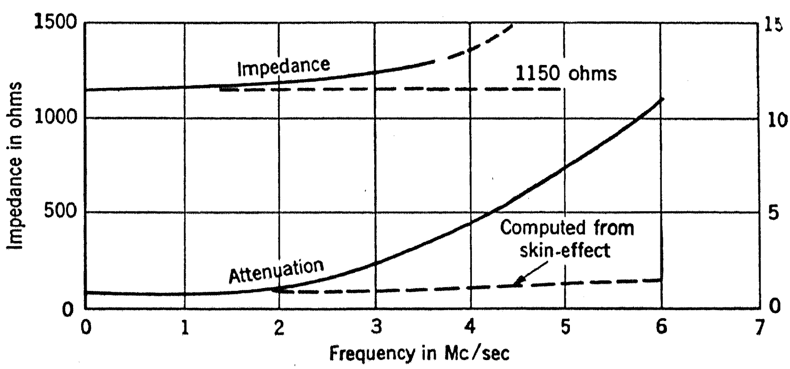
modification of the Formex-braid-covered lines manufactured by the General Electric Company. The introduction of patches permits making the line thicker, and thus shorter and with somewhat less attenuation for a given delay. This line is wound on a tube of insulating material



(a)



(b)



(c)

FIG. 6·12 (a, b, and c).—Continuously wound delay line with floating patches and Formex braid.

having an outside diameter of $\frac{1}{4}$ in. The patches on the core are each 0.001 in. thick and 0.345 in. wide, and they are spaced $\frac{7}{16}$ in. from center to center, with about 0.02-in. gap between them; they are covered with one layer of 0.001-in. ceresin-wax-impregnated condenser paper. The line is closely wound with AWG No. 40 Formex HF and covered with a tight-fitting braid of 195 strands of 0.005-in. Formex-insulated copper wire. The delay for a 10-in. length is 1 μsec with an impedance of about 1150 ohms. The delay characteristic of several models $10\frac{1}{16}$ in. long is plotted in Fig. 6·12*b*. Since finished braid was drawn over the windings of these models and tightened by hand, ground capacitance, delay, and impedance varied slightly, which will explain the unevenness of curve No. 3 of Fig. 6·12*b*. The transmission loss and impedance characteristics of such a line are plotted in Fig. 6·12*c*.

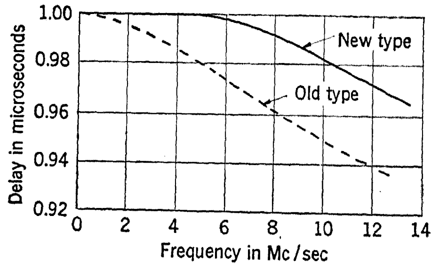
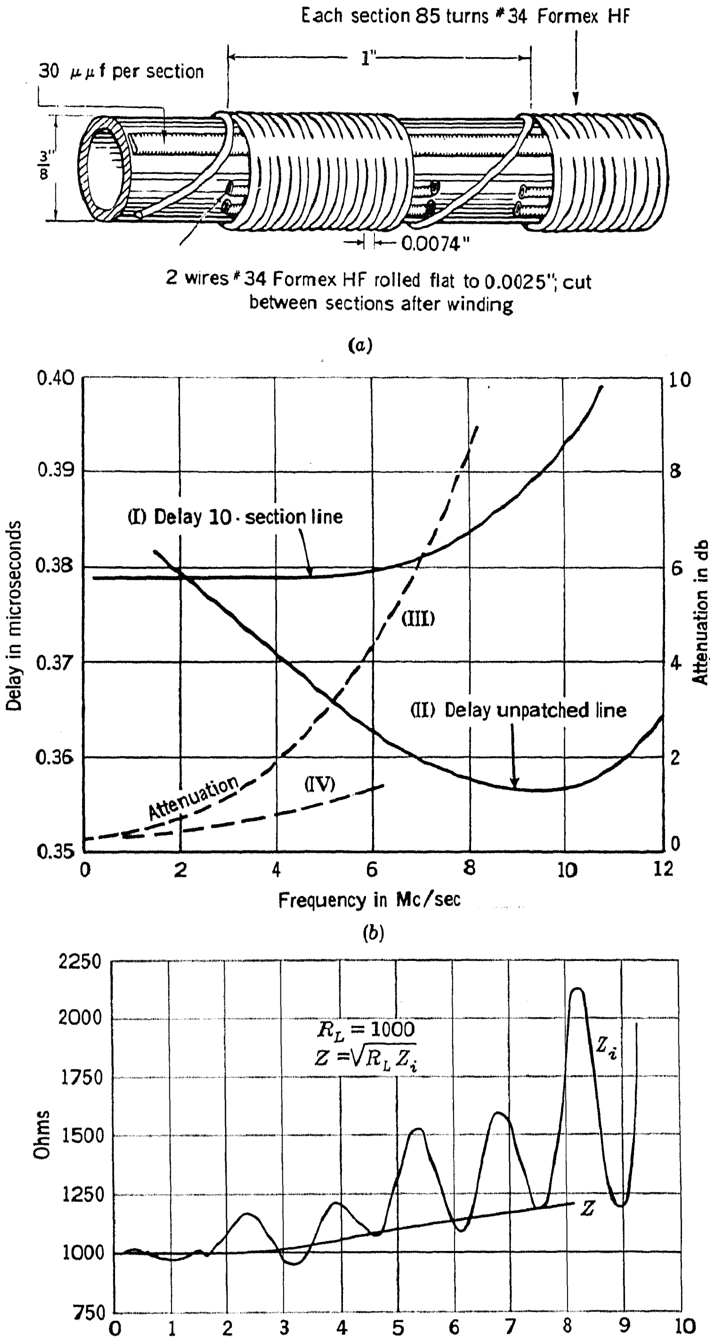


FIG. 6·13.—Effect of metal-paste dielectric.

The original design of the GE delay line shown in Fig. 6·4 has been improved[1] by the introduction of distributed bridge capacitance. The coiled conductor is coated after winding with a paste of fine aluminum powder in polystyrene coil dope. It is then covered with plastic tape and Formex wire braid as before. The metal powder paste is a substance of very high dielectric constant. Inserting it between the coiled and the braided conductor will thus change the capacitance between them only slightly, and this change is easily compensated by a slight adjustment in the dimensions of the dielectric tape. However, the capacitive coupling between distant turns, which before had been suppressed by the close-fitting metal braid, is now very much increased and the resulting benefits to the phase response are analogous to those derived from floating patches. Fig. 6·13 shows the delay response of the improved GE line, compared with that of an old line. The attenuation of the line is not perceptibly affected by this modification.

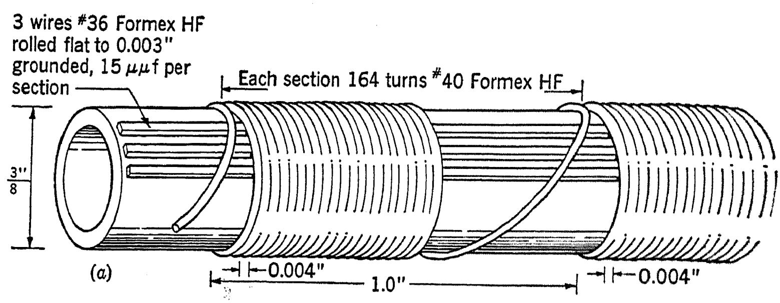
To ensure signal delay without spurious echo pips, lines of the distributed-parameter type may be modified by winding them in sections. Figure 6·14 shows a signal delay line, wound in sections with l/d equal to 1.6. Each section yields a delay of about 0.038 μsec, at an impedance of

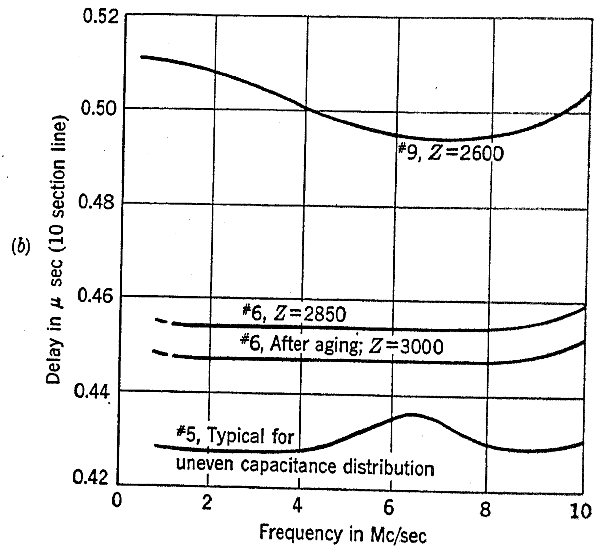
[1] See Blewett and Rubel paper cited on p. 193.



Input impedance of 10 section delay line

(c)





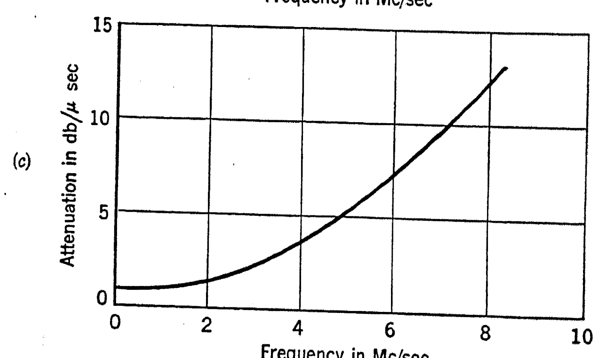


FIG. 6·15 (a, b, and c).—Line with sectionalized winding and three ground strips.

1000 ohms. The line is wound with AWG 34 Formex HF wire on bakelite tubing of $\frac{3}{8}$-in. OD with $\frac{1}{32}$-in. wall; each section of 85 turns is closely wound; sections are spaced 1 in. center to center. The capacitance to ground of 39 $\mu\mu$f per section is provided in this model by four strips of AWG No. 20 Formex HF wire rolled to 0.010-in. thickness and placed between core and coil. Three strips of AWG No. 34 Formex HF wire rolled to 0.0025 in. are also inserted; after winding, the latter strips are cut between each two coils to form the floating bridge capacitances. It is both reasonable and convenient to make the number of equalizing patches equal to that of the sections. The width and exact location of the cut between coils is immaterial. The delay response of 10 sections is plotted in Fig. 6·14*b* with that of an unpatched line for comparison (Curves I and II). The transmission loss of such lines is also plotted in Fig. 6·14*b* Curves III and IV, the latter computed from skin effect. The input impedance and the characteristic impedance of a very similar line of 0.35-μsec delay is plotted in Fig. 6·14*c*.

Another model of a signal delay line wound in sections is illustrated in Fig. 6·15. This line is designed for a delay of about 0.05 μsec per section at an impedance of 3000 ohms. It was wound on bakelite tubing of $\frac{3}{8}$-in. OD and $\frac{1}{32}$-in. wall thickness, with 164 close-wound turns of No. 40 Formex HF per section, 10 sections spaced 1 in. center-to-center. The ground capacitance of 14·5 $\mu\mu$f per section was provided by inserting three grounded strips under the winding, each a No. 36 Formex HF wire rolled flat to 0.003 in. Since winding of fine wire by hand does not make for closely predictable ground capacitance, those of different models varied, resulting in impedances from 2600 to 3100 ohms, and delays from 0.43 to 0.51 μsec (Fig. 6·15*b*). Capacitances may also be uneven within a line as is shown in Curve No. 5, and cause a hump in the delay characteristic. There is no visible equalizing capacitance provided with these lines since the distributed coil capacitances are of just the right value for the 3000-ohm model. The delay of Curve No. 9 drops since the greater delay time of 0.051 μsec per section needs more equalization; similar models for higher impedances already have too much natural coil capacitance, resulting in steadily rising delay characteristics. The transmission-loss characteristic of the line for 3000 ohms is plotted in Fig. 6·15*c*; the input impedance resembles that of Fig. 6·14*c*.

Models of delay lines with iron-dust cores have been made but are still in an experimental stage.

6·3. Lumped-parameter Delay Lines. *Characteristics.*—For very low impedances or for very high voltages, it is more convenient to lump the ground capacitances than to distribute them along the winding. Also,

where suitable condensers are chosen, the attenuation, due largely to dielectric losses, is appreciably lower in lumped-parameter than in distributed-parameter delay lines and the temperature coefficient usually is only approximately 0.01 per cent per degree centigrade.

The delay in a simple low-pass filter network comprising only series inductances and shunt capacitances rises appreciably with frequency ω according to the equation

$$T = \frac{2}{1 - \left(\frac{\omega}{\omega_0}\right)^2}. \tag{10}$$

It has therefore long been the practice to improve the delay characteristic of the ordinary low-pass filter by the use of sections with a value of

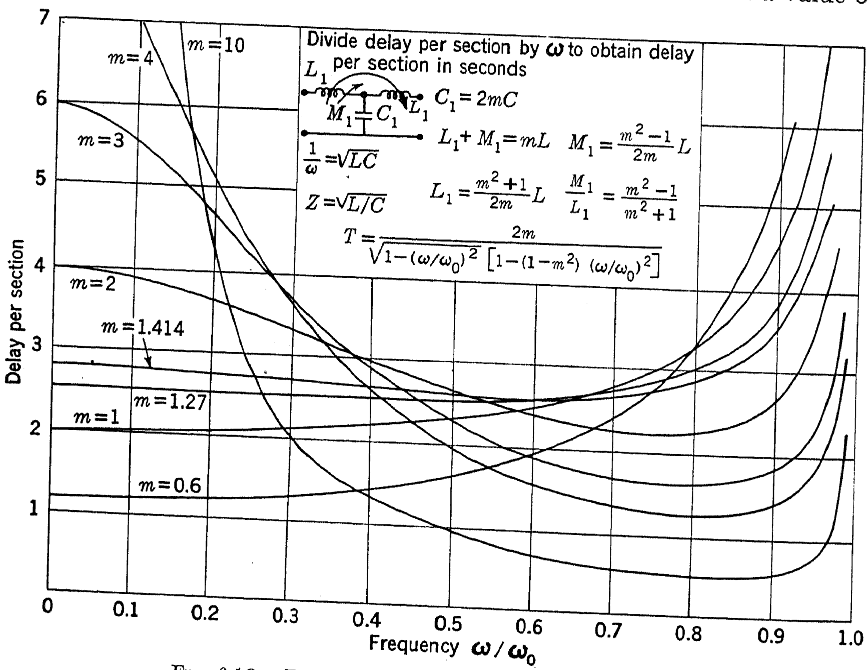


FIG. 6·16.—Delay in m-derived low-pass filter sections.

$m = 1.27$. The time delay of an m-derived filter is given in the following equation,

$$T = \frac{2m}{\sqrt{1 - (\omega/\omega_0)^2}\,[1 - (1 - m^2)\,(\omega/\omega_0)^2]}. \tag{11}$$

Time delay is plotted for various values of m in Fig. 6·16. The choice of $m = 1.27$ is arrived at by arbitrarily equating the delay at $\omega = 0$ with that at $\omega = 0.5\omega_0$; but it can also be seen from Fig. 6·16 that this

choice offers the flattest possible delay characteristic up to about $0.55\omega_0$. As shown in Fig. 6·16, each m-derived filter section is built with one inductance L_1 on each side of the condenser C_1, and the pair of inductances is coupled with a mutual inductance M_1, whereby

$$C_1 = 2mC = 2.54C,$$
$$L_1 = \frac{m^2 + 1}{2m} L = 1.03L,$$

and

$$\frac{M_1}{L_1} = \frac{m^2 - 1}{m^2 + 1} = 0.237. \tag{12}$$

Delay equalization depends critically on the coupling between the two coils L_1. Apparently the most convenient way to control the equalization is to wind both coils as a continuous close-wound or pitch-wound single coil with a tap at the center, and to choose the core diameter, wire gauge, and thickness of insulation so that the coupling between the two halves is correct. It can be shown that this method requires only that the ratio of the length to the diameter of the whole coil equal 1.55. In a proper coil the total inductance is

$$2.54L = 2L_1 + 2M_1 = \frac{4m^2}{m^2 + 1} L_1 = 2.46L_1.$$

The total inductance is thus 1.23 times larger than the sum of the halves L_1. This ratio depends only on the values of coefficients k which can be found from a plot of Nagaoka's constant k for the inductance of a solenoid by searching for a pair of values k_1 and k_2 such that $k_2 = 1.23\ k_1$ when $l_2/d = 2l_1/d$. Such a pair occurs only once, for $k_1 = 0.62$ and $k_2 = 0.77$ with $l_2/d = 1.55$.

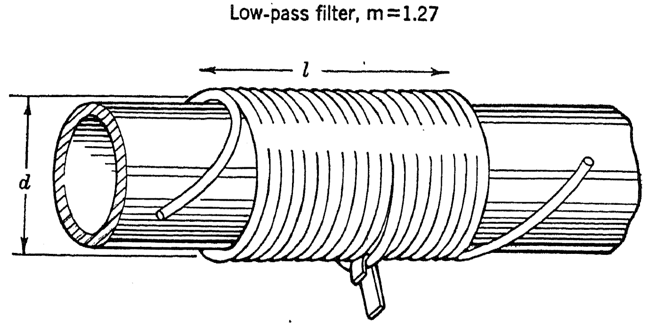
The design then requires the choice of an average coil diameter and pitch such that the desired total inductance $2.46L$ is obtained with a coil 1.55 times longer than its average diameter d, to be found by satisfying both Eqs. (13) and (14).

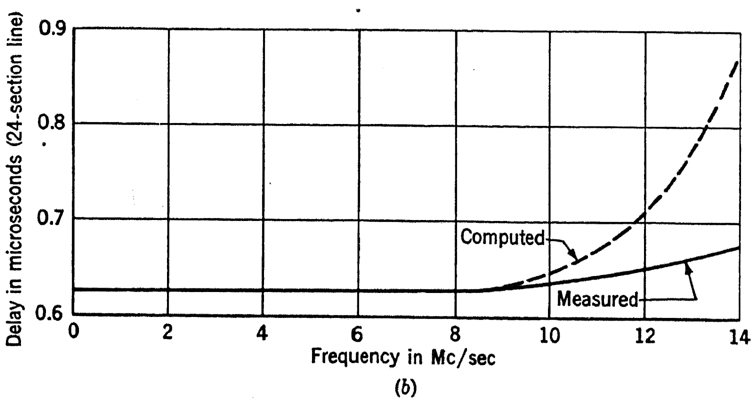
$$2.46L_1 = \frac{0.77 \times 10^{-9}\pi^2 n^2 d^2}{1.55} = 5 \times 10^{-9} n^2 d, \qquad \text{henry, cm,} \tag{13}$$

and

$$l = nw. \tag{14}$$

Satisfactory coils for delay networks wound according to the specifications of Eqs. (13) and (14) are illustrated in Fig. 6·17. These coils were wound on cores $\frac{3}{16}$ to 1 in. in diameter, for impedances from 70 ohms to over 1000 ohms and for voltages up to 25,000 volts. Capacitances were not only selected to tolerances of ± 1 per cent, but also were placed in the order





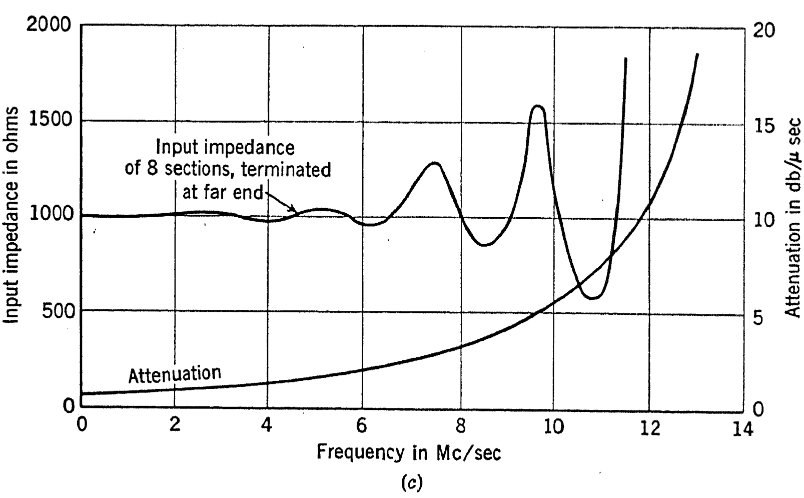


FIG. 6·17 (*a*, *b*, and *c*).—Lumped-parameter delay line.

of their value so as to minimize impedance changes between adjacent sections. Results measured on a typical network of 24 sections with $m = 1.27$ are plotted (Fig. 6·17b); the impedance is 1000 ohms; the nominal cutoff frequency, 16 Mc/sec; the delay per section, 0.025 μsec. In this as in all similar cases, the delay characteristic stays flat over a somewhat larger frequency range than that computed from Eq. 11 (see Fig. 6·17b). The attenuation (Fig. 6·17c) in such a filter with mica or ceramic condensers is much lower than in delay lines of the distributed parameter type because of the much lower dielectric losses. The input impedance, shown for a line without input termination in Fig. 6·17c, is very flat, rising slowly after $0.5\omega_0$. Conventional methods of termination can be used for further improvements. The most satisfactory results were obtained with an m-derived half section, as shown in Fig. 6·18.

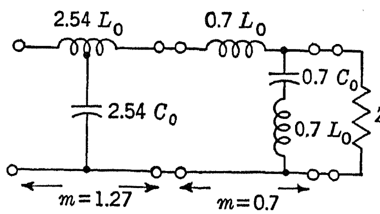


FIG. 6·18.—Termination of lumped-parameter line.

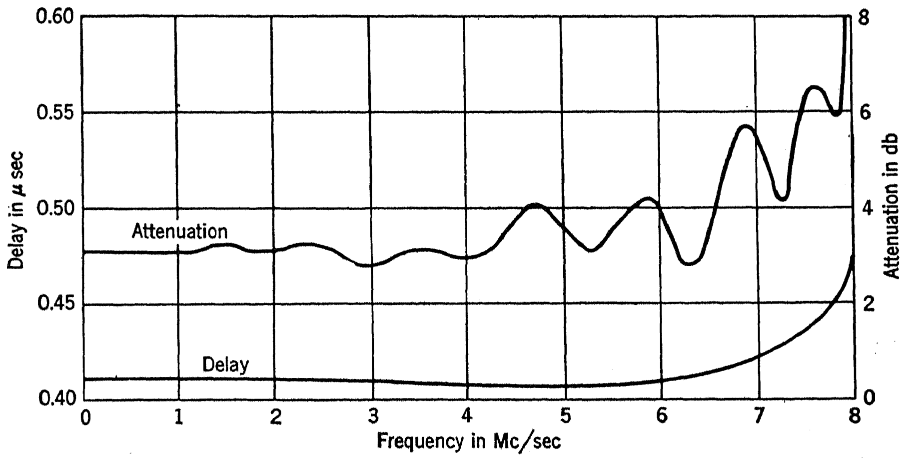


FIG. 6·19.—Characteristics of 8 sections of Raytheon delay line type CRP 14 ABD.

A delay network of this type suitable for long delay of trigger pulses is manufactured by the Raytheon Manufacturing Company as type CRP 14 ABD. The line has an impedance of 75 ohms. Each section of the line is connected to the next by a spade lug and terminal screw, and therefore any desired delay up to 2.4 μsec can be set in steps of 0.05 μsec. Six blocks of eight sections with $m = 1.27$ are housed in a common metal case about 15 by 3 by 8 in. Each center-tapped coil of 47 turns is wound to 3.46 μh on a threaded ceramic core of 0.375-in. $\pm$ 0.002-in. diameter. The capacitors are silver-mica condensers of 750 $\mu\mu f$ $\pm$ 2 per

cent. The nominal cutoff frequency is 8 Mc/sec. The delay and attenuation observed on a block of eight sections are plotted in Fig. 6·19 (the attenuation includes a loss of 3 db due to the measuring setup).

Design of this type of delay networks is based on the assumption that there is no appreciable coupling between sections. In practice, this

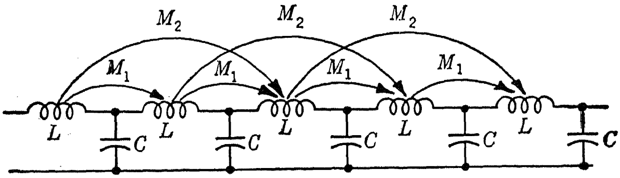


FIG. 6·20.—Mutual inductance between sections of lumped line.

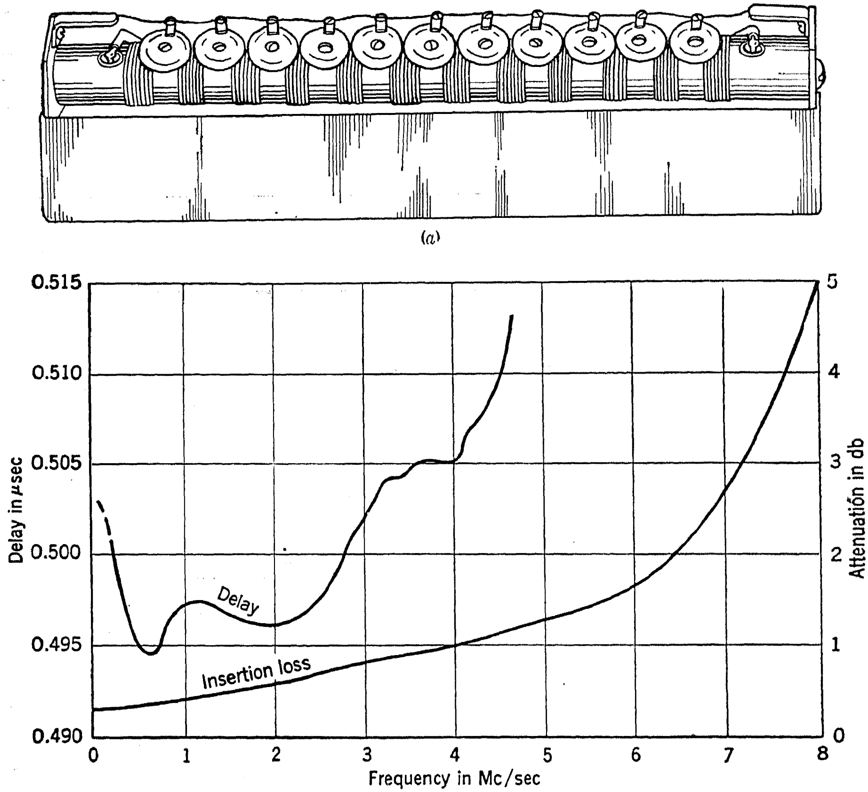


FIG. 6·21 (*a* and *b*).—BTL type D-168435 delay line.
(NOTE: "attenuation" in Figs. 6·21 and 6·22 should read "insertion loss.")

condition is fairly well satisfied if there is a clear space equal to the coil diameter between each two sections. This requirement may be objectionable if only very little space is available. A number of delay net-

works that require very little space have been developed in the Bell Telephone Laboratories.

These networks consist only of series coils and shunt condensers such as would correspond to an ordinary low-pass filter with $m = 1$. But the relatively short coils of each section are wound with rather close spacing on a common core and the coupling to the adjacent section M_1 and even to the next one, M_2, becomes significant as shown in Fig. 6·20. In these

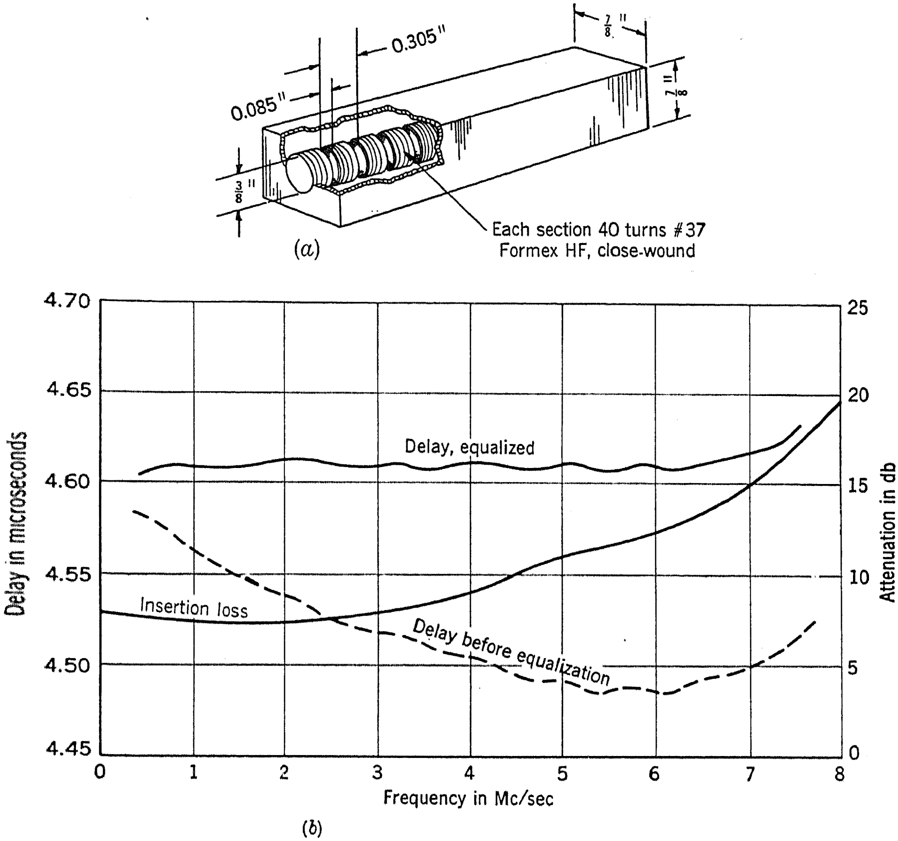


FIG. 6·22 (a and b).—BTL type D-172597 delay line.

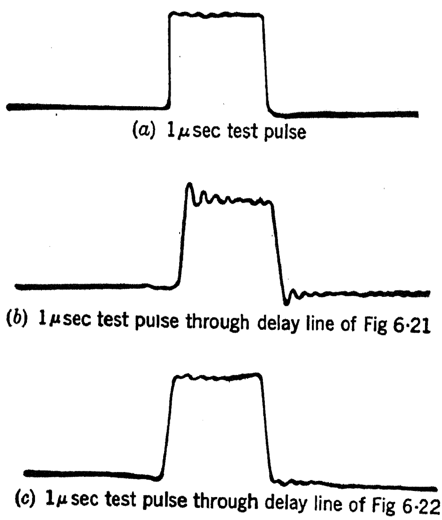
lines the relative amounts of inductance L and mutual inductances M_1 and M_2 are controlled by choice of three parameters:

1. the ratio of length to diameter of each coil,
2. the spacing between sections, and
3. in some models, the closeness of the short-circuited turn provided by a rather narrow metal case.

When properly proportioned, such lines have time-delay responses that oscillate only slightly around the desired value up to 55 per cent of the nominal cutoff frequency. One or two phase-correcting T-sections may be added to the whole delay line for further delay equalization.

Typical Lumped-parameter Delay Lines.—The specifications of two typical lines are as follows:

1. BTL type D-168435. (This line is used in portable oscilloscopes. In Fig. 6·21*a* it is sketched lifted out of and on top of its case.)
   a. Case: $6\frac{1}{2}$ in. by 1 in. by $\frac{7}{8}$ in.
   b. Impedance: $Z = 550$ ohms
   c. Delay: $T = 0.5$ μsec
   d. Nominal cutoff frequency: 9.5 Mc/sec
   e. Phase: equalized within $\pm 3°$ up to 4 Mc/sec
   f. Attenuation: 1/4 db at low frequencies rising to 1 db at 4 Mc/sec (see Fig. 6·21*b*)
   g. Coil: 12 sections wound to 5 per cent tolerance
   h. Capacitors: button-type silver-mica condensers ± 5 per cent



(*a*) 1μsec test pulse

(*b*) 1μsec test pulse through delay line of Fig 6·21

(*c*) 1μsec test pulse through delay line of Fig 6·22

FIG. 6·23.—Waveforms of BTL delay networks. Rise time is 0.2 μsec for (*b*) and 0.1 μsec for (*c*).

2. BTL type D-172597. (This line is characterized by long delay with very little distortion. It has negligible crosstalk.)
   a. Case: 9 by $3\frac{3}{4}$ by $2\frac{3}{4}$ in. with individual screen cans for each length of line controlling mutual inductances (and helping prevent crosstalk between them)
   b. Impedance: 430 ohms
   c. Delay: 4.6 μsec in 144 sections and 2 equalizing T-sections
   d. Nominal cutoff frequency: 12.5 Mc/sec

e. Phase: equalized to 7 Mc/sec to within $\pm 4°$, (In Fig. 6·22*b*, the broken line applies to the line before 2 *T*-sections were added.)

f. Attenuation: raised to 7 db at low and medium frequencies, then rising slowly beyond 4 Mc/sec, as in Fig. 6·22*b*

g. Coils: Dimensions of the windings and case are shown in Fig. 6·22*a*

h. Capacitors: silver-mica button condensers ± 5 per cent.

The distortion of 1-μsec pulses transmitted through these last two lines is shown in Fig. 6·23.

CHAPTER 7

SUPERSONIC DELAY LINES

BY H. B. HUNTINGTON

The supersonic delay of electrical signals is accomplished by changing electrical impulses into sonic impulses through some appropriate transducer and, at the end of a fixed path in a transmitting medium, converting the sonic impulses back into electrical signals by a second transducer. For frequencies in the megacycle range, which has been used for the most part in this work, quartz crystals are the most satisfactory transducers. Liquids, such as water and mercury, have been used as transmitting media, but transmission through solid material will probably be developed in the future.

These delay devices may be divided into two general categories according to purpose: those that delay a video signal such as a trigger or range marker, which then reappears in differentiated form, and those that faithfully delay a pulsed carrier. For faithful delay a certain bandwidth is needed and the design requirements for this category are therefore somewhat more complex than for the other type.

A discussion of experimental devices is not included in this chapter. Attention should, however, be directed to one particularly promising possibility now under development—namely, delay in fused quartz blocks, which is discussed in some detail in Vol. 20, Sec. 13*a*·7, Radiation Laboratory Series.

7·1. Summary of Supersonic Delay-line Formulas. *Velocity of Propagation.*—The derivation of supersonic delay-line formulas has been treated in more detail elsewhere.[1] In mercury the delay time[2] is 17.52 μsec/in. at 20°C. The temperature variation in this neighborhood is $+0.0052$ μsec/in. per °C.

$$D = [17.52 + 0.0052(T - 20°\text{C})]l, \tag{1}$$

where D is the delay in microseconds and l the length of line in inches.

[1] A forthcoming article by the author (to be published in *Jour. Franklin Inst.* under the title "Ultrasonic Delay Lines," I and II) provides a systematic development and a more complete discussion of these relations. The reader is referred to this article for the theory in its most general form.

[2] R. Jacobson, "A Measurement of Supersonic Velocity in Mercury at 15 Megacycles per Second as a Function of Temperature," RL Report No. 745, Sept. 20, 1945.

The velocity of propagation in water has a temperature coefficient of the opposite sign from that of mercury (and of most other fluids investigated) in the region of room temperature. The curves for the two velocities as a function of temperature actually cross at $12\frac{1}{2}$°C. See Fig. 7·1. The temperature coefficient of velocity in water, however, vanishes at $72\frac{1}{2}$°C, where the velocity is maximum. By mixing water with other fluids in proper proportions, the temperature of the velocity maximum can be lowered in a predictable manner.[1] G. W. Willard of the Bell

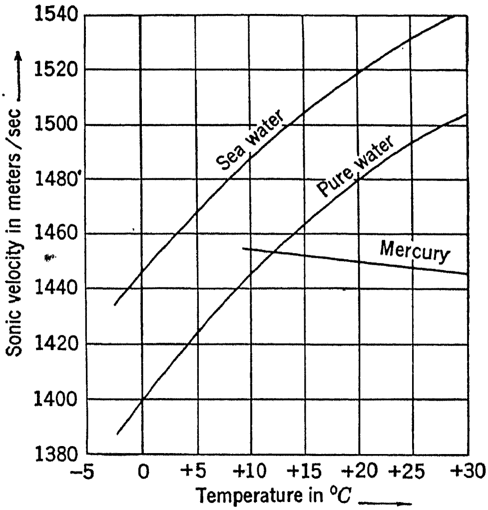


FIG. 7·1.—Sonic velocity as a function of temperature.

Telephone Laboratories at Murray Hill has investigated supersonic velocity in several such mixtures, particularly water solutions of ethanol, of methanol, and of ethylene glycol.[2]

Resonant Frequency.—The resonant frequency of an X-cut quartz crystal is given by

$$f \text{ (in Mc/sec)} = \frac{2.86}{d}, \tag{2}$$

where d is the thickness of the quartz plate in millimeters.

[1] G. W. Willard, "Compounding Liquids to Give Zero Temperature Coefficient of Ultrasonic Velocity," BTL Report 593, Sept. 9, 1941.

[2] G. W. Willard, "Ultrasonic Absorption and Velocity Measurements in Numerous Liquids," *Jour. Acoustical Soc. Am.*, **12**, 438 (January 1941). See also A. Giacomini, *Pontif. Acad. Sci. Acta*, **6**, 87 (1941); T. Derenzini and A. Giacomini, *Ricerca Sci.*, **13**, 27, 242 (1942); G. W. Willard, *Jour. Acoustical Soc. Am.*, **19**, 235 (January 1947); and A. Giacomini, *ibid.*, **19**, 701 (July 1947).

Electrostatic Capacitance.—The electrostatic capacitance of a 10-Mc/sec X-cut quartz crystal (if edge effects are neglected) is given by the formula

$$C = 91.5 \times S \quad \mu\mu\text{f}, \tag{3}$$

where S is the excited area of the crystal measured in square inches. This quantity is inversely proportional to crystal thickness or directly proportional to its resonant frequency.

Bandwidth of a Piezoelectric Crystal.—The acoustic impedance of a material is the product of its density ρ times its velocity v for the propagation of the mode under consideration. Generally speaking, the frequency response becomes broader as the acoustic impedances of the media with which it is in contact are increased.[1] As an illustrative example consider the case where the crystal is in contact with the same medium on both sides. The Q of the crystal alone (exclusive of any shunt circuit which tunes out the electrostatic capacitance) is given by

$$Q = \frac{n\pi}{4} \frac{\rho V}{\rho_1 V_1}, \tag{4}$$

where ρV refers to the piezoelectric crystal, $\rho_1 V_1$ to the adjoining media, and n is the order of the harmonic at which the crystal is being driven.[2]

Beam-spread Formula.—To estimate the order of magnitude for beam-spreading and also to establish mechanical tolerances for proper alignment, it is useful to remember the formula for the half-angle θ of the cone subtended by the first minimum in the free-space diffraction pattern at large distances.

$$\sin \theta = 1.22 \frac{\lambda}{d}, \tag{5}$$

where d is the diameter of the transmitting crystal and λ is the wavelength in the transmitting medium. Nearly all the emitted energy falls inside this cone.

Insertion Loss.—There are two contributions to the insertion loss.

1. Voltage loss through impedance mismatch. For a line using a perfectly reflecting crystal (air-backed) the ratio of output voltage V_o to input voltage V_i is given by

$$\frac{V_o}{V_i} \approx \frac{8R_r}{k\rho_1 v_1} \quad \text{if} \quad k\rho_1 v_1 \gg R_r, \tag{6}$$

[1] Huntington, *op. cit.*, Part 1, Sec. B.

[2] In the journal article by Huntington, *op. cit.*, the quantity Q is defined in a particular way. It is the Q of the simple series-resonant circuit whose amplitude response exhibits the same curvature in the region of resonance as does the amplitude response of the transducer element.

where R_r is the value of the receiver input. For an X-cut, 10-Mc/sec quartz crystal in contact with mercury,

$$k\rho_1 v_1 = \frac{84{,}000}{S} \qquad \text{ohms,} \tag{7}$$

where S is again the excited area measured in square inches. The quantity k is primarily a function of the crystal and varies inversely as the square of its resonant frequency.

If the same medium is on both sides of the crystals, there is a resulting loss of 12 db, 6 db for each crystal.

2. Attenuation. (Empirical relations.) Free-space attenuation in mercury is given by

$$\text{loss in db} = (0.012 \pm 0.002)f^2 l, \tag{8}$$

where f is the frequency in Mc/sec and l is the length in feet. Tube attenuation is given by

$$\text{loss in db} = \frac{0.054\, f^{1/2} l}{d}, \tag{9}$$

where d is the inner diameter of the tube in inches. This value for tube attenuation applies only to smooth internal surfaces such as glass tubing. For rougher surfaces the attenuation is larger and increases more rapidly than $1/d$ with decreasing bore.

7·2. Crystal Design Problems. *Crystal Thickness.*—Equation (2) gave the relation between resonant frequency and thickness of crystal plate in the direction of the electric axis. When transmission of video signals is involved, one customarily uses crystals whose fundamental resonance is in the region of 1 to 10 Mc/sec, depending somewhat on the width of video pass band and the rise time desired. When a modulated carrier is used, one employs crystals whose resonant frequency lies near the frequency of propagation. Considerable latitude is possible, however, in the choice of crystal thickness, particularly if mercury is employed for the transmitting medium. The large acoustic impedance of mercury will lower the Q of the crystal circuit according to Eq. (4).

Rather thick crystals may be used for these frequencies (5 to 30 Mc/sec) if the crystals are driven at their odd harmonic frequencies. This involves, however, a loss in voltage by the same factor as the number of the harmonic—that is, $1/n$th the effective voltage at the crystal driven at the nth harmonic. However, for those delay lines where the bandwidth must be maintained constant, there is a compensating effect. The live capacitance of the thicker crystal driven at the nth harmonic

will be smaller by a factor of $1/n$. If there were only the live capacitance, then the loading resistor which insures the proper bandwidth for the shunt resonant circuit could be increased by a factor, n. In turn the applied or received voltage would be effectively increased by a factor n since the generator and the line act as high-impedance sources. Under such circumstances there would be no disadvantage involved in using harmonic operation. Actually, since the existence of additional stray capacitance at the driving and receiving crystals prevents complete compensation, harmonic generation is not generally preferred at those frequencies for which crystals operating on the fundamental can be conveniently handled.

Active Area.—In determining crystal size the method of mounting and the size of the inner diameter of the tube are important factors. In general one plans to make the active crystal area equal to the inner cross section of the tube. Under these conditions a crystal perpendicular to the tube axis will propagate a nearly plane wave down the tube. Although such a plane wave is an oversimplification, experience has shown that satisfactory reproduction of pulse shape is generally achieved. One generally chooses the size of the active area of the crystal so that the live capacitance will be comparable with the stray capacitance when the latter has been reduced to a minimum. It can be shown that the matching of live to stray capacitance gives a maximum ratio of output voltage to input current for a delay line which is passing a fixed bandwidth and feeding into a low-impedance load. For best signal-to-noise ratio, the optimum value of the live capacitance is somewhat greater than the stray capacitance, depending on the characteristics of the first stage of the amplifier at the receiver crystal.

Technique of Crystal Mounting.—A satisfactory crystal mounting must fulfill the following fundamental requirements. The crystal must be adequately supported and protected so that it will not bend or break. It must be aligned with the tube axis to an accuracy of about $0.2\ \theta$ where θ corresponds with the angle of beam spread introduced in Eq. (5). Finally provision must be made for attaching electrodes to the crystal surfaces in such a way as not to interfere with its sonic operation. This requirement necessitates plating at least one face for transmission with nonconducting liquids. The usual procedure is to let the plated surface make contact against a retaining ring in the end assembly and so act as the grounded side of the crystal.

In the crystal mounting for Line A[1] of Fig. 7·2, the crystal is backed by mercury, which obviates the necessity for any plating on that side. The large acoustic impedance of the mercury also loads the crystal and

[1] Table 7·1 gives the important characteristics of eight delay lines, including those referred to in the text by capital letters.

widens its pass band, thereby assuring rapid rise of the trigger with a minimum of "ringing."

In the so-called "Shockley line," used for trigger delay in range units, the crystal is again loaded by being soldered to a brass backing.

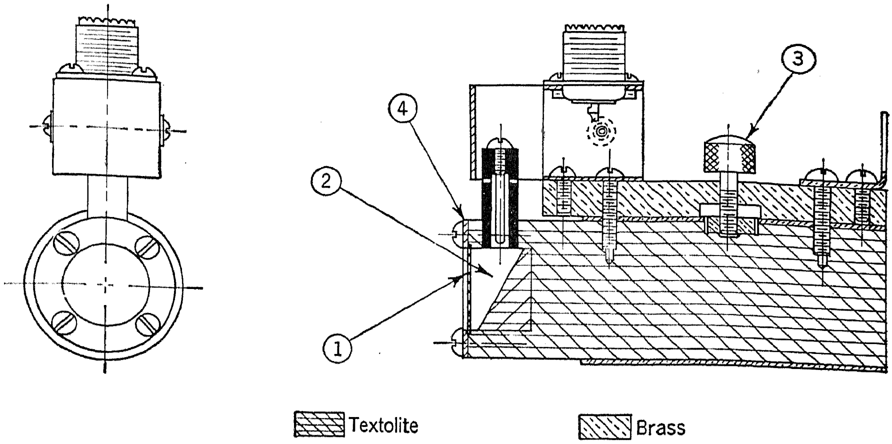


FIG. 7·2.—Crystal assembly for Line *A*. (1) A 10-Mc/sec crystal, plated on the front side, is lacquered to Textolite piece. (2) This space holds the backing mercury. The main part of the assembly slides inside a tube containing the water. (3) This screw elevates the piece into which it is threaded and so holds the assembly fixed in the tube. Wire leads connect the uhf fitting to the mercury well and to the (grounded) clamp ring (4).

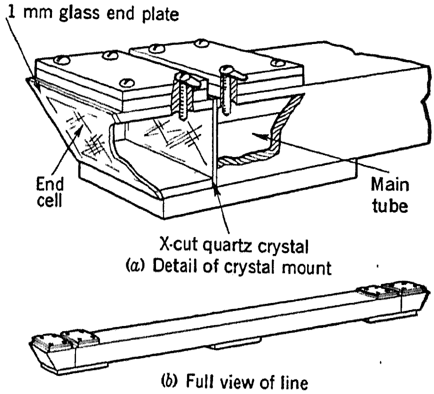


FIG. 7·3.—Liquid delay line for experimental system.

For those lines that were built to give faithful reproduction of pulse shape after delays of approximately 500 μsec, an additional requirement is the elimination of unwanted multiple echoes. This can be done by absorbing nearly all the energy incident on the crystal in the medium on the other side. Since the crystal at resonance acts as a half-wave section, it is necessary only to match acoustic impedances on both sides of the crystal. For the mercury lines this matching was first done by

putting mercury also in back of the crystal. Figure 7·3 shows how this was done for one of the early lines used for an experimental system. The beam that was transmitted into the backing mercury cell was broken up and dissipated by the glass plate set at an angle to the direction of the beam.

When the crystal mounting with absorbing backing was taken over into actual system use, some provision had to be made to prevent pressure transients caused by shock from breaking the crystal. If the fluid on both sides of the crystal completely filled its container, leaving no air space into which it could be driven by sudden shock, equality of pressure would be maintained under mechanical test but not under thermal variation. In the case of Line *B* the problem was solved to a large extent by inserting a coiled steel capillary which acted as a connecting link between the completely filled chamber in the line and a partially filled chamber in the loading plug. The short-time transients were damped by the viscous forces in the capillary walls, but slow thermal variations altered the mercury level in the cap chamber and produced no net pressure change (see Fig. 7·4). The particular procedure for crystal mounting in this case is shown in Fig. 7·5. As is indicated by the captions, the crystal was lacquered into a carefully machined recess in the bakelite end block. This was in turn lacquered to the end of the delay line and bolted in place. The oblique surface marked "deflecting plug" serves to break up the absorbed beam in the same way as was done in the experimental line, Fig. 7·3.

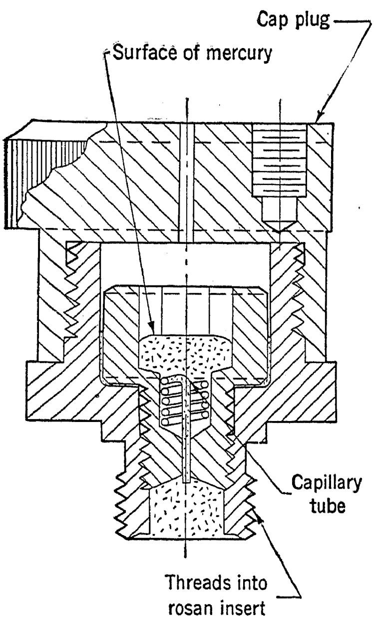


FIG. 7·4.—Mercury inlet with capillary loading.

Later some modifications in absorbing backings for crystals were introduced in a delay line for which a steel backing piece was used with a deeply cut sawtooth surface (see Fig. 7·6). The tops of the teeth supported the crystal's back surface, and the space between the teeth was filled with mercury. The supporting steel area should be too small to give appreciable reflection but should still support the crystal adequately under variation of static pressure as well as under sudden shock. It was found that this requirement was necessary in airborne operation.

There is another promising possibility for an absorbing backing that

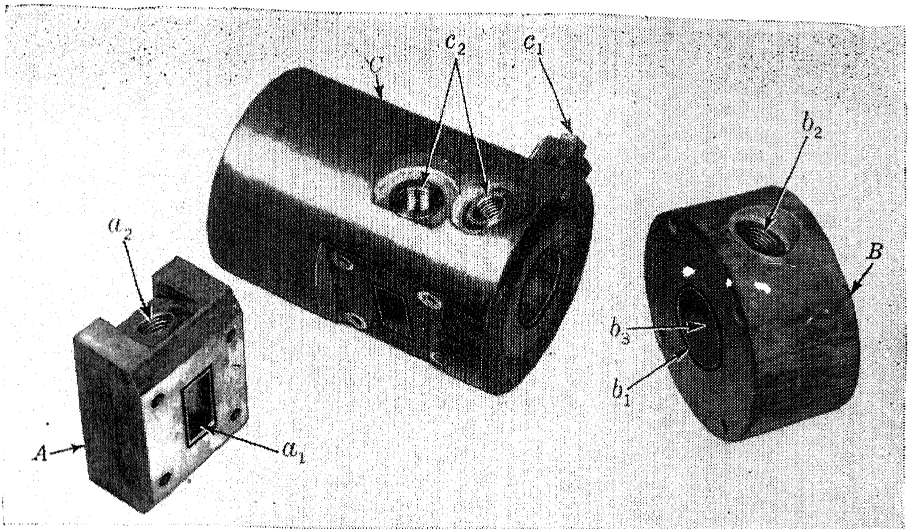


FIG. 7·5.—Assemblies for supporting crystals in Line B. A, trigger crystal mounting block, containing cavity a_1 for rectangular trigger crystal, which is backed by mercury in the trigger shock well. This is filled through the loading duct a_2, which is closed by a capillary bleeder plug and connector cap. B, receiver crystal mounting block, with cavity b_1 for round receiver crystal, and shock-well loading duct b_2 similar to a_2. The rear surface b_3 of the shock well is inclined to the axis of the beam (see text). C, end fitting, to which A and B are bolted. The pinion shaft protrudes through the fitting c_1, providing adjustment of trigger reflector position. Filling ducts c_2 give access to front faces of crystals, permitting cleaning while the line is loaded. (*Courtesy of Raytheon Manufacturing Company.*)

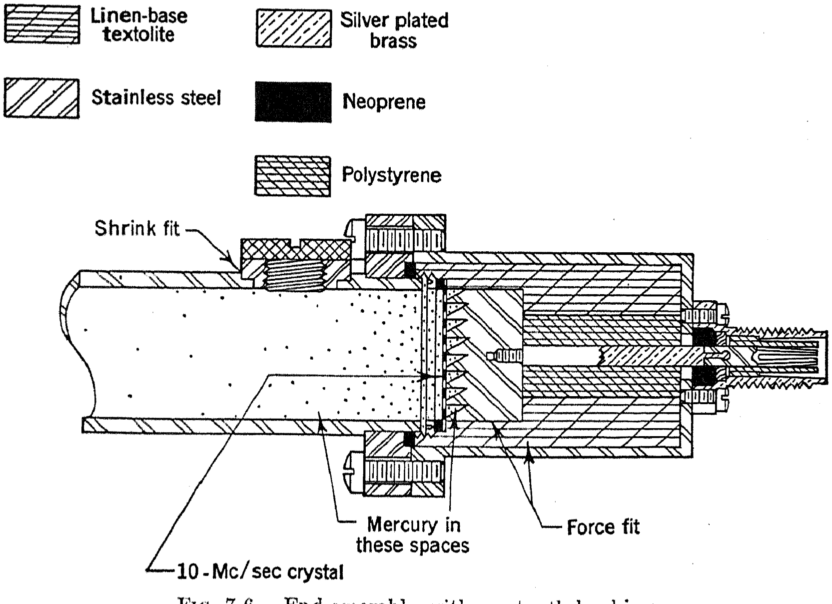


FIG. 7·6.—End assembly with sawtooth backing.

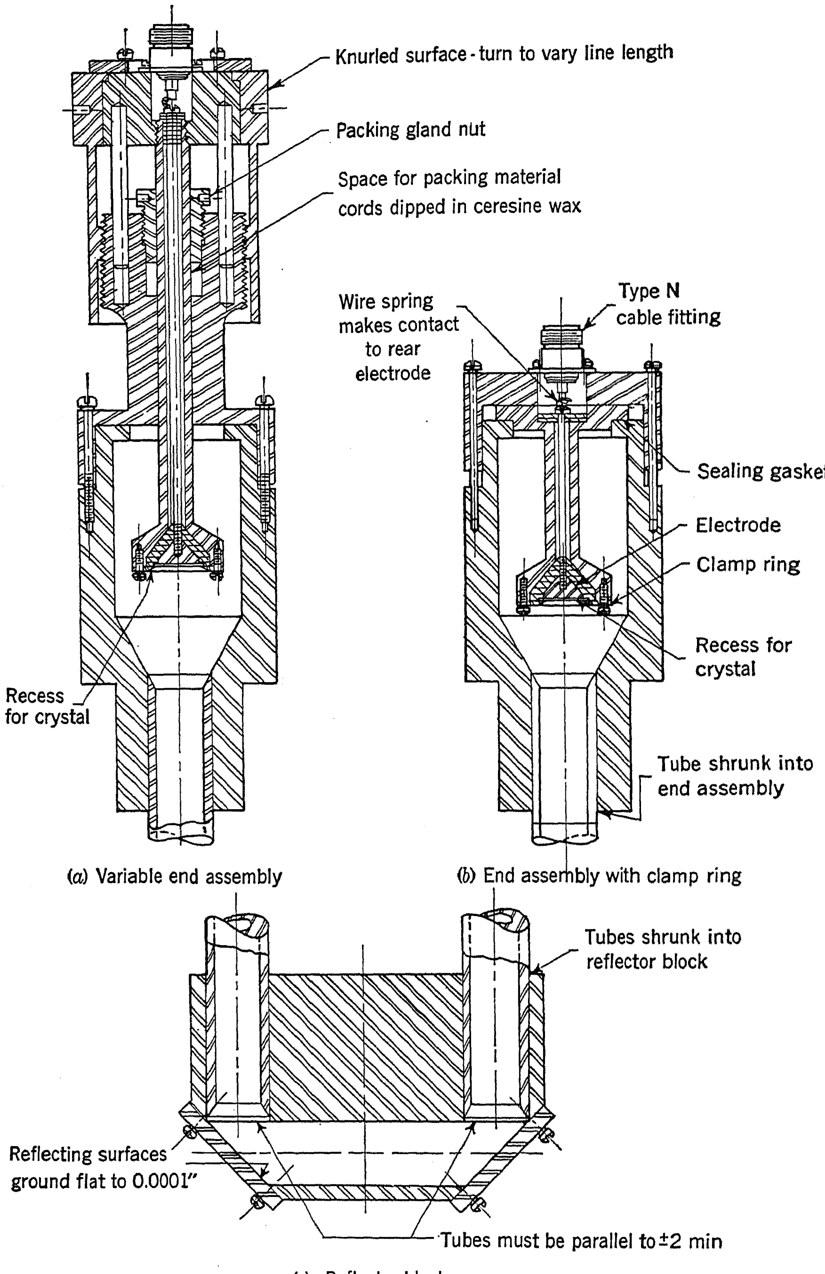


FIG. 7·7.—End assemblies and reflector block for Line D.

has not yet been incorporated into any system application—namely the use of a solid backing that is a good match for the transmitting medium. For mercury a good match can be secured with the crystal soldered to hard lead (6 per cent Sb). Preliminary measurements have shown that under these conditions the reflected amplitude is about 18 db less than in the case when the crystal is supported by a dry electrode. The hard lead has two advantages: it is machinable, and it readily attenuates the absorbed signals. For effective soldering, the crystals must first receive a composite evaporated film of chromium and silver according to the

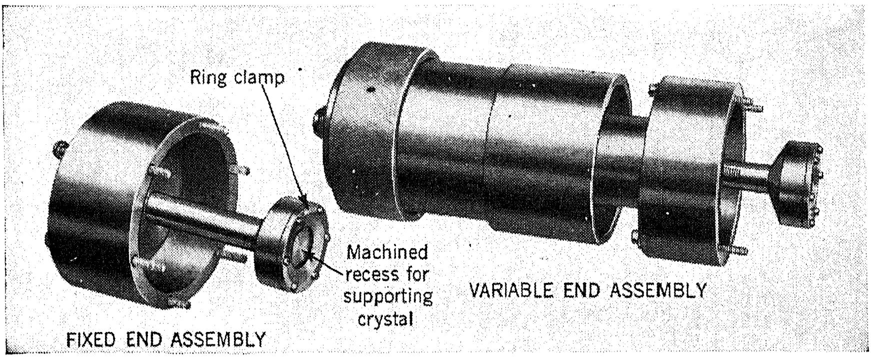


FIG. 7·8.—End assemblies for Line D.

process developed by Professor John Strong of California Institute of Technology. Rose's metal is suggested as a suitable solder to be used with a flux made of water, glycerine, and tartaric acid. Once the crystal has been soldered onto the lead electrode the latter can be cemented into a dielectric and incorporated into the end assembly. Precaution should be taken to prevent the mercury from getting in contact with the solder or the lead. The final step is to machine the aligning surfaces so that the crystal will be perpendicular to the tube axis.

With the work on longer lines it became less necessary to use absorbing backings.[1] It became practical to use dry steel electrodes, which reflect nearly all of the incident energy, and to take advantage of the resulting increased transmission of longer lines (see discussion of insertion loss, Sec. 7·1). The problem of maintaining the crystal aligned, flat, and uniformly supported, was simply solved in many cases by employing a clamp with gaskets to hold the crystal in place on the electrode. The end assembly used in Line *D* is a good example of this construction (Figs. 7·7 and 7·8). There the 10-Mc/sec crystals were set in recesses in the mounting and held in place with ring clamps. Polyethylene washers under the clamps made mercury-tight seals to prevent short-circuiting.

[1] For quantitative discussion, see Vol. 20, Sec. 13a.2, Radiation Laboratory Series.

Reflecting crystal mountings were also used in Line C because, although the delay was short, the carrier frequency was high enough (30 Mc/sec) to attenuate completely all reflected signals. Because of the extreme thinness of the quartz crystals required for fundamental

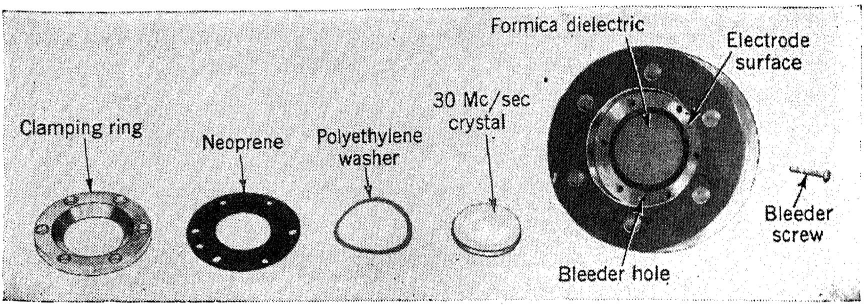


FIG. 7·9.—End assembly for Line C.

operation at this frequency, it was extremely difficult to mount them so that they would not bend and deform the beams. Here again the crystals were supported by ring clamps, as shown in Figs. 7·9 and 7·10. No recess was used but the crystal covered the electrode exactly. The electrode was ground flat to 0.0001 in., otherwise the superimposed crystal would show very evident distortion in optical reflections from its surface. Often the electrode surface would be flat enough to permit one to observe Newton's rings between its surface and the bottom surface of the crystal. A ring of thin polyethylene outside the crystal had its top surface flush with the upper crystal surface. On top of both surfaces and sealing to both was placed a ring of neoprene held down by the ring clamp. The bleeder screw shown in Fig. 7·9 serves as a device for eliminating air bubbles on the surface of the crystals. With the line in a horizontal position the screw is loosened until a fine jet of mercury passes the threads. All bubbles also escape simultaneously. The screw is then tightened and usually lacquered to make a tight seal.

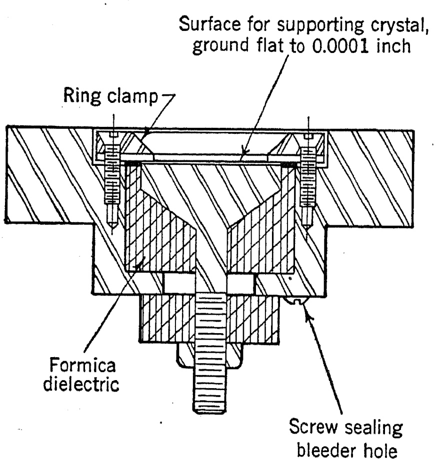


FIG. 7·10.—End assembly for mounting 30-Mc/sec crystals, Line C.

A similar construction was also employed in the crystal mountings for Line E. A type-N fitting, Fig. 7·11, was added at the back and the

thickness of the dielectric (formica) around the electrode was increased to reduce the stray capacitance. Since this line operated at a lower frequency (15 Mc/sec), it was more important to keep the stray capacitance at a minimum. (At lower frequency the line capacitance is reduced and it becomes more difficult to match it to the stray capacitance.)

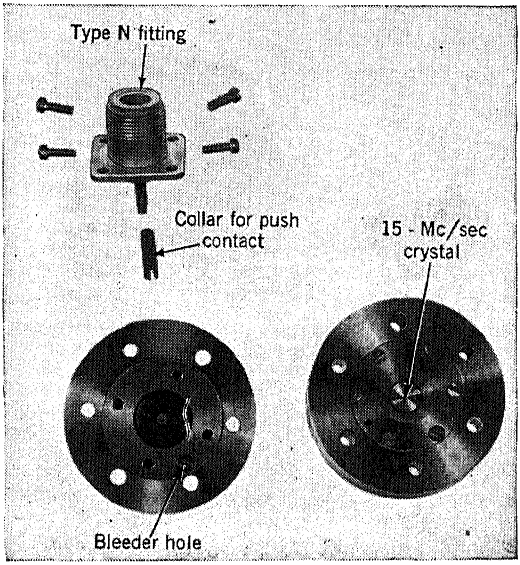


FIG. 7·11.—End assembly, Line *E*.

7·3. Line-design Problems. *Electrical and Mechanical Stability.*—Where great stability of delay is required, it is often advisable to maintain the delay device at a constant temperature at which the thermal coefficient of velocity is zero. This has been done successfully in the Shockley delay tank for trigger delay with a mixture of water and ethylene glycol at 55°C, and in the water delay line built by H. Grayson in England for MTI purposes, held at $72\frac{1}{2}$°C. It is also possible to vary the line length to compensate for this effect as has been done with Line *C*.

Thermal variations introduce a problem in the expansion of the transmitting fluid. The solution to this problem for Line *B* was described in Sec. 7·2. Reference to the end assembly (Fig. 7·8) for Line D shows an air space provided in back of the crystal mounting. Line *C* was provided with a reservoir cup (Fig. 7·12) partly filled with mercury. In Line *E* the reservoir was a pressure bellows completely filled with mercury (Fig. 7·13).

In any system that contains an air chamber there is always a possibility that air may become trapped against the surface of the crystal and thus change its live capacitance and the sonic transmission into the

medium. This effect is particularly serious with mercury since it does not wet the quartz and bubbles have a tendency to cling. With Lines C and E, bleeder holes were employed to allow bubbles trapped against the quartz to escape. It is necessary to "bleed" both end assemblies

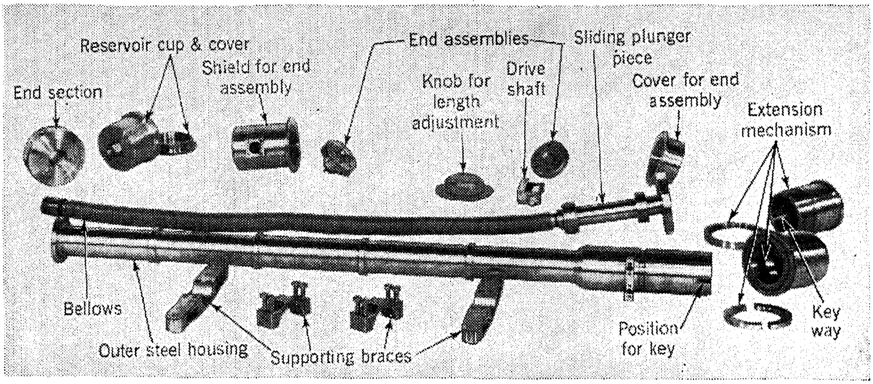


FIG. 7·12.—Line C disassembled.

after each filling of the line. With Line B, slanting holes were provided (Fig. 7·5) at the surface of each crystal. Their purpose is to allow cleaning of the crystal surfaces without disassembling the line, but they also serve to eliminate any chance for air pockets.

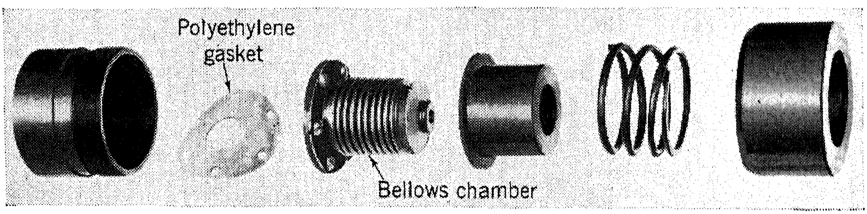


FIG. 7·13.—Pressure bellows for Line E.

With liquid lines the need for securing tight seals is obvious but may still cause difficulties. Long mercury lines when put on end will exert internal pressures of several atmospheres. It requires good engineering and careful workmanship to make them leakproof.

Folded Lines.—For longer delays it is often inconvenient to use a straight line for the complete length. The usual procedure is to employ two or more lengths of pipe interconnected by corner reflectors. A corner reflector consists generally of two reflections through 90°. Two separate examples suffice to show the type of construction involved. In Line D two pipes are press-fitted into holes bored into the reflector block as shown in Fig. 7·7c. Two stainless-steel plates, ground flat to 0.0001

in., are attached to the block, at 45° to the beam, and serve as the corner reflector. For Line E (Fig. 7·14) the parallel pipes are welded into flat end plates. The corner reflector (Fig. 7·15) is made of a single piece of

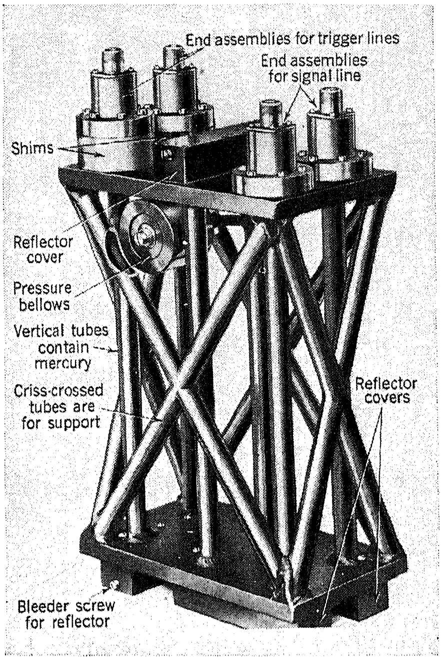


FIG. 7·14.—Line E.

stainless steel. The reflecting surfaces are plated with 0.015-in. chromium and ground flat. This piece is bolted to the end plate and is contained in a cover piece which is sealed to the end plate with a neoprene washer.

Since 45° is outside the critical angle for any transmission of energy from mercury into steel one would expect very little loss on reflection at this angle. Actually, however, considerable attenuation may be present. H. J. McSkimin of the Bell Telephone Laboratories at Murray Hill has investigated this effect systematically and found practically no loss for very smooth steel or polished glass reflectors. He also found negligible losses (less than 0.1 db per reflection) for rough surfaces such as are obtained by lapping a steel surface with 160-mesh

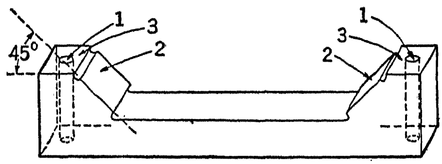


FIG. 7·15.—Corner reflector for Line E. (1) Clearance holes for bolts which hold reflector to end plate. (2) Chromium-plated reflector surfaces, flat to 0.0001 in. (3) Aligning surface. Plane 2 must be accurately at 45° with plane 3.

Carborundum. For surfaces of intermediate texture, however, a large loss of perhaps several decibels usually occurred. The general explanation of this phenomenon, as propounded by McSkimin, is that since the mercury does not wet any surface with which it does not amalgamate small depressions in the reflecting surface give rise to air bubbles. If part of the beam is reflected from the steel and part from the air bubbles, there will be a phase difference between the two parts and destructive interference will occur. The phase of the beam reflected from the steel for a 45° reflector differs by nearly $\frac{\pi}{2}$ radians from the phase of the incident beam.[1] The phase of the displacement associated with the part of the beam undergoing reflection from the air—that is, low impedance—is reversed. From this it follows that the destructive interference could have a maximum effect of nearly 3 db per reflection.

Mechanical Tolerances.—As a general rule, such tolerances are required that the maximum total deviation from parallelism of the crystal surfaces will be about 0.2θ where θ is the angle of beam spread. One must of course take the same care with the aligning of reflectors as with crystal mountings. An accurately made corner reflector—that is, 90°—need be aligned only in the angle perpendicular to the plane of the corner. In a water delay line this was accomplished by a manual adjustment. For Line *E* close tolerances were demanded for the 90° angle between the reflecting surfaces and also for the 90° angle between the plane of the reflection and the aligning surfaces which rest on the face plates. The face plates were, in addition, machined to be flat and parallel. The use of the three corner reflectors in the signal line has one interesting consequence, that the parallelism requirement for the face plates was unnecessary as far as performance of the signal channel was concerned.

In any mechanically variable line machining tolerances must be carefully specified to insure that the moving part is subject only to translation, because any slight rotation will affect the alignment correspondingly.

Variable Lines.—Variable trigger delay lines have been used with water or water solutions. In the Shockley line the transmitting crystal could be translated by a carefully threaded screw. From the rotation of this screw, radar range could be read. The transmitting fluid was completely enclosed in the delay tank.

The movable feature for Line *A* was a much cruder affair. The long copper tube was open down the top in a wide slit and one crystal assembly could be slid up and down the tube by hand. A setscrew was provided to maintain an adjustment.

In the water delay line of Fig. 7·16 a variable feature has been introduced by a "trombone" construction which can be adjusted from

[1] H. B. Huntington, *op. cit.*

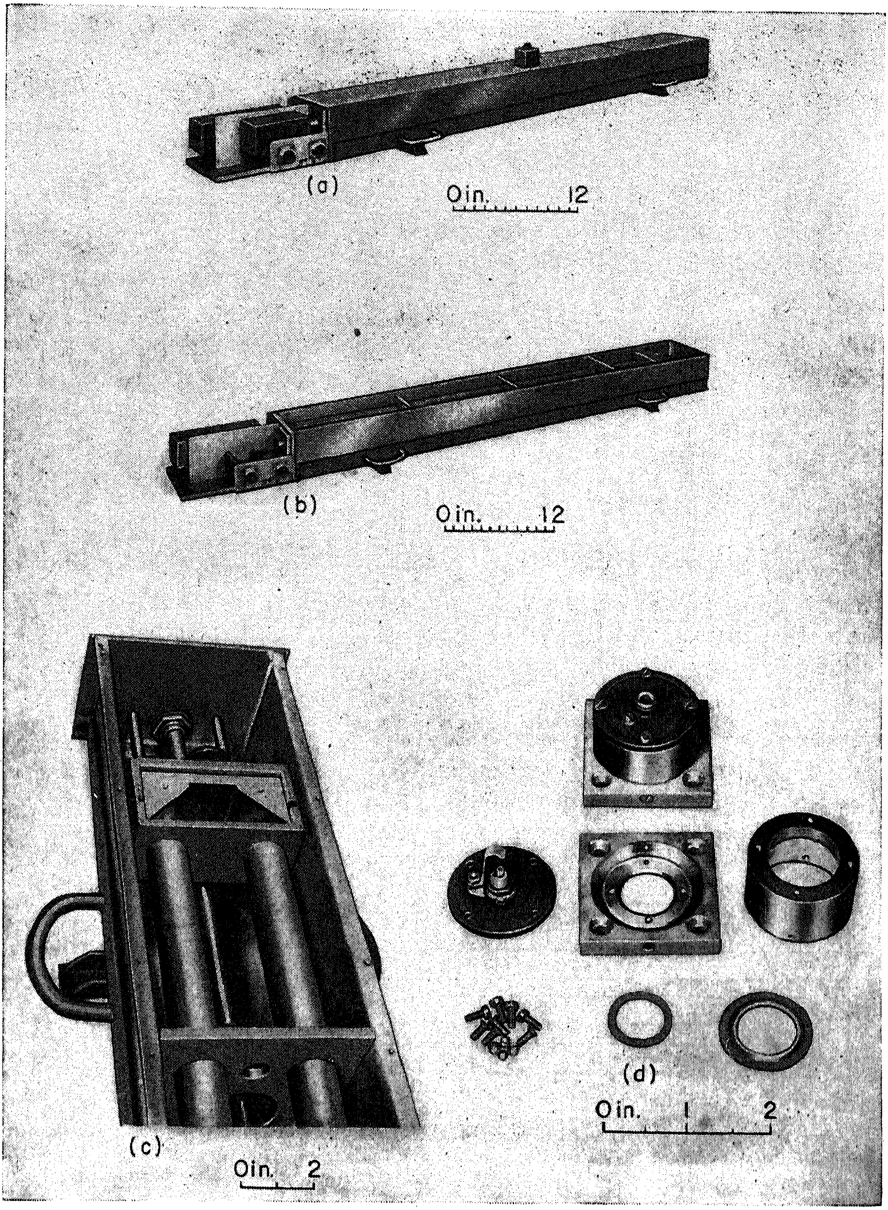


FIG. 7·16.—Water delay line. (*a*) Line assembled; (*b*) line, cover removed; (*c*) "trombone" construction and reflector block; (*d*) crystal mount disassembled. (*Courtesy of Royal Aircraft Establishment.*)

outside the tank. Since the pipes themselves are surrounded by water there is no sealing problem involved.

At present there are two techniques for making variable mercury

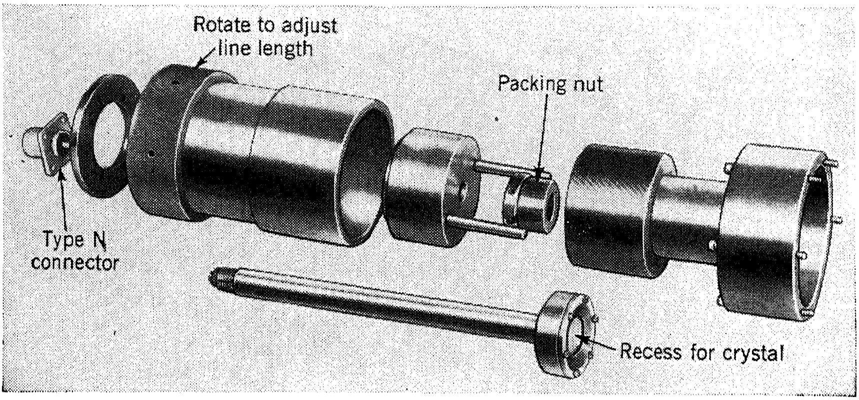


FIG. 7·17.—Variable end cell for Line *D*.

delay lines for field use. In one the position of a crystal or reflector is controlled by a mechanical drive. Part of the coupling shaft is actually immersed in the liquid and a packing cell prevents leakage of the fluid.

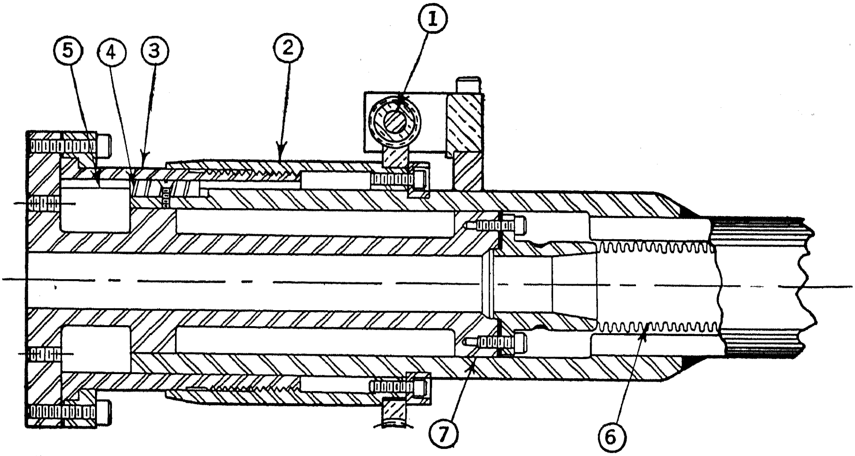


FIG. 7·18.—Drive for extending bellows in Line *C*. A drive shaft (1) with geared-down ratio 36: 1 causes collar (2) to rotate without translation. This action causes a translation of a second collar (3) at the rate of $\frac{1}{40}$ in. per revolution. The rotation of collar (3) is prevented by a key (4) bolted to the main tube and sliding in keyway (5). The plunger piece (5) moves with collar (3), thereby extending or contracting the bellows (6) to which it is bolted. Very precise machining of surfaces (7) is required to maintain alignment during translation.

For mercury an effective packing gland is made of cord dipped in ceresine wax and tightly compressed around the shaft. Such a procedure was used in Line *B* to vary the position of a 45° reflector and in Line *D* to

move a crystal mounting parallel to itself. The design used in the latter case is depicted in Figs. 7·7, 7·8, and 7·17. The second technique involves a bellows construction which allows the driving mechanism to be completely outside the space occupied by the mercury. Stainless-steel bellows are used with Line C (Figs. 7·12 and 7·18).

Third Crystal.—In Line B, a third crystal inserted in the side of the line just in front of the receiver crystal (Fig. 7·5) is used to pick up the 8-Mc/sec components of a strong video pulse sent down the line. This signal is then amplified and used as a trigger for repetition-rate control. A variable 45° reflector in the line serves to pick off a fraction of the incident intensity and deflect it to the third crystal. A similar construction was used in another delay line but was later discarded. The action of that variable reflector is illustrated in Fig. 7·19.

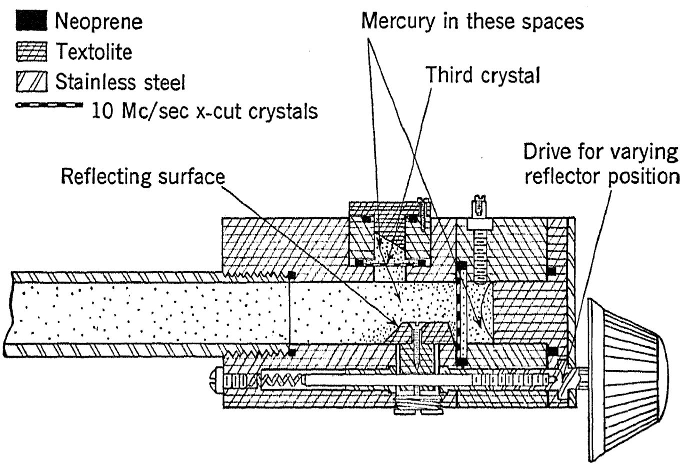


FIG. 7·19.—Variable reflector and third crystal.

7·4. Calculation of Insertion Loss.—In this section Eqs. (6) to (9) are applied to calculate the insertion loss to be expected for a particular example; Line E. The following specifications are pertinent:

1. $17\frac{1}{2}$-Mc/sec crystals used with 15-Mc/sec carrier.
2. Tubing of $\frac{3}{8}$-in. ID.
3. 6 reflections, 3 corner reflectors.
4. $R_r = 500$ ohms.
5. Length of total mercury path, 4 ft, 9 in., or 1000 μsec.

It follows then that

$$k\rho_1 v_1 = \frac{28{,}000 \text{ ohms}}{S} = 250{,}000 \qquad \text{ohms} \tag{6a}$$

since $S = 0.111$ in.^{2}

$$\frac{V_o}{V_i} = \frac{8R_r}{k\rho_1 v_1} = \frac{1}{63} \text{ or } 36.0 \quad \text{db voltage loss.} \tag{7a}$$

$$\text{For free-space attenuation } 0.012 \times (15)^2 \times 4\tfrac{3}{4} = 12.8 \quad \text{db.} \tag{8a}$$

$$\text{For tubular attenuation } \frac{0.054}{\frac{3}{8}} \sqrt{15} \times 4\tfrac{3}{4} = 2.7 \quad \text{db.} \tag{9a}$$

This gives for the insertion voltage loss 52 db exclusive of loss at the reflecting surfaces, which might amount to 5 to 10 db.

If one wishes to find the insertion loss in available power—that is, the ratio of available power at the delay-line output terminal to the available power at the output of the driving circuit—one must replace Eq. (6) by

$$\frac{P_o}{P_i} = \frac{64R_rR_t}{(k\rho_1 v_1)^2},$$

where R_t is the impedance of the driving circuit.

7·5. Assembly and Maintenance. *Cleaning.*—All metallic parts of a mercury line that come in contact with the liquid must be carefully cleaned before assembly by immersion in some grease solvent such as xylene, toluene, or carbon tetrachloride. Any residual oil or grease will cause the formation of a scum on the surface of the mercury that will affect transmission adversely, particularly if it comes in contact with the surfaces of the crystals. Polyethylene and neoprene gaskets should be cleaned in alcohol since they would be damaged by the toluene, etc. Care should be exercised to handle cleaned parts as little as possible on assembly. Crystals in this frequency range are usually supplied waxed to glass plates. They can be slid off after gentle heating and should be carefully cleaned to remove all wax. One recommended technique for this cleaning is to put the crystal on a flat surface, such as plate glass, and scrub with surgical gauze dipped in xylene. Mercury that contains only mechanical impurities can be cleaned satisfactorily by passing it through a small hole in the apex of a cone of filter paper. If the mercury is contaminated by metallic impurities, the filtering will not remove the amalgams. Generally a short time later more of the amalgam will become oxidized and scum will re-form on the surface of the mercury.

Filling.—Filling procedures differ according to line construction. When a long tube is filled from one end opposite a crystal mounting, it is advisable not to pour the mercury vertically before the surface of the crystal has been covered, because crystals have been cracked by freely falling mercury.

Folded lines usually require a rather prolonged ritual of shaking, tilting, and filling piecemeal to eliminate unwanted air bubbles. End assemblies equipped with "bleeder" holes usually require "bleeding"

after every refilling and possibly even after being transported from one place to another.

Transportation of mercury delay lines raises a problem because of risk of leakage or crystal breakage. In some instances it has been the procedure to ship delay lines empty and to fill in the field. Steel bottles are recommended for the transport of the mercury used in filling.

If the mercury used in filling has just been filtered, or violently shaken, or subjected to mechanical shock, or poured into the line in a thin stream, the supersonic transmission appears to suffer anomalous attenuation. If left alone, the excess attenuation decreases, rapidly at first but more slowly later, with the result that it may take several hours or even a day or so to reach its normal value. The effect is believed to be caused by small air bubbles in suspension in the mercury. In this connection it should be remarked that a sharp blow on a delay-line tube containing mercury will produce a similar increase in the attenuation. Experiments by H. J. McSkimin of Bell Telephone Laboratories show that air bubbles are the cause of this effect. Because the mercury does not wet the wall surface, a considerable quantity of air is occluded between the mercury and the steel. Vibrations of the wall after being struck drive the air out into the mercury in the form of small bubbles.

Measurement.—Measurement of the capacitance at the end assembly is a very useful procedure in trouble-shooting because it shows up air bubbles, crystal fracture, or other causes of instability in the crystal mounting. The measurement is easily done at low frequency on a Q meter.

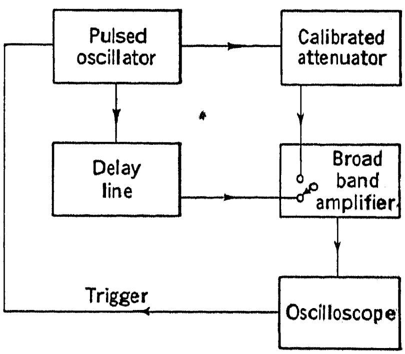


FIG. 7·20.—Block diagram for voltage-loss measurement.

The insertion voltage loss of a delay line is a quantity that can be measured directly and gives important design information. It consists in determining the ratio of input voltage to output voltage (into a specific impedance level) of the delay line. One procedure is given in the block diagram of Fig. 7·20.

The measurement consists in matching the delayed signal through the delay line with an undelayed pulse through the attenuator and recording the attenuator reading. The following points in the procedure should be noted:

1. The outputs of delay line and attenuator are in general not in parallel but a switch is provided so that the amplifier input can be

shifted from one to the other. This arrangement simplifies the shielding problem, since pickup across the delay line does not affect the delayed signals and the switch prevents it from reaching the attenuated pulse. The attenuator itself should be well shielded and whatever pickup there is across the switch should be small. If the size of this pickup voltage can be measured, one can deduce that the limits of accuracy of measurements, at a power level 20-db higher, are ± 1 db.

2. For reproducible measurements the frequency of the oscillator should be checked. This is particularly important for lines having considerable free-space attenuation because this quantity varies as the square of the frequency.
3. If a synchroscope or A-R scope is employed, the measuring equipment should be adjusted so that delayed and undelayed pulses can be thrown on the same area of the scope alternately. Accurate matching is then possible and the inspector can compare the two pulses as to general character, shape, time of rise, etc. He should also look for extra (unwanted) signals at high gain.
4. The electrical inputs of the delay line and attenuator should be in parallel so that the input voltage will be the same across both.
5. From the form of Eq. (6) it is apparent that a value for the insertion loss in voltage has meaning only when the impedance of the receiver is specified. If this impedance is about a few hundred ohms or greater, it will be necessary to tune out fairly accurately (presumably with tunable coils) the capacitance at the receiving crystal. However, if the specified impedance is in the neighborhood of 70 ohms, a single fixed-tuned coil in the right range will suffice for all lines of the same design. A measurement made at one impedance level in this range can be transformed to another impedance level by considering the crystal output as a high-impedance source.

Transmission loss is affected by temperature mainly in the attenuation terms. As might be expected from the temperature coefficient of the viscosity, the free-space attenuation of water decreases markedly as the temperature is raised. This effect has not been carefully measured for mercury.

The signals in mercury lines are not so sensitive to changes in thermal environment as those in water lines. Thermal gradients in mercury that arise from changes in thermal environment will cause changes in signal intensity. For unfolded lines that are not completely rigid the signal can be restored by bending the line down in the middle. Such deformation increases the relative path length for that part of the supersonic beam in the lower portion of the tube where the mercury is cooler and

the velocity is faster. The bending in this manner tends to counteract the refraction. (It may be noted in passing that such bending of lines in every direction and at thermal equilibrium is a very simple test of mechanical misalignment.)

There is some indication that changes in pressure affect transmission loss, possibly by compressing air bubbles in the mercury or in contact with the crystal. The effect has been observed with Line E on the bench and in the air. A similar effect was also reported for Line C when it was subjected to a roll of about 15° on shipboard. It is possible that such pressure effects present a fundamental limitation of liquid delay lines for MTI purposes in shipborne and airborne applications.

Maintenance.—Maintenance routine, like filling procedure, differs from line to line. Instances of crystal fracture are rare, and, generally speaking, the main problem of delay-line maintenance appears to be in keeping the mercury clean.

With Line B, slanting holes in the tube top give direct access to the crystal surfaces so that they can be cleaned directly even while in contact with the mercury. Line C can be readily disassembled and the mercury cleaned by filtering. This is fortunate since mercury contamination proved to be a serious problem in some of the delay lines that were sent out into the field. An attempt has been made to locate the origin of this difficulty and some contamination has definitely been traced to the stainless-steel bellows.[1] A thin coat of lacquer on the inside of the bellows appears to be a simple and effective preventive.

7·6. Compilation of Delay-line Specifications.—Table 7·1 of Delay-line Information includes most of the readily available information on seven delay lines as engineered for actual use, two for trigger delay and five for the faithful delay of pulses. Photographs of the completely assembled delay lines are included in this section. In general the specific entries in the table have already been treated in detail, thus no additional discussion is needed here.

Experimental delay lines and lines built for experimental systems have been omitted. Short fixed lines of about 5- to 10-μsec delay, although not of sufficient complexity to warrant inclusion in the table, were widely employed in system application and should be mentioned.

A drawing of a 6-μsec glass delay line is shown in Fig. 7·24. It was used to give a series of pulses appearing at odd multiples of the fundamental delay, 6 μsec. The crystals were fastened to the glass block by a thin layer of paraffin. This layer served to maintain acoustic contact between the quartz and glass. A brass electrode was pressed against the back of each crystal by a phosphor-bronze spring.

[1] H. B. Huntington, "Notes on Contamination of Mercury by Stainless Steel," RL Report No. 935, March 1, 1946.

TABLE 7·1.—TABLE OF DELAY-LINE INFORMATION

	Designation of delay line							
	Shockley line	Line *A*	Line *B*	Line *C*	Line *D*	Line *E*	Line *F*	Water line (RAE)
Purpose	Trigger delay		Cancellation with MTI					
Manufacturer	Western Electric	Radiation Laboratory	Raytheon	Robertson Tool Co.	Radiation Laboratory	Robertson Tool Co.	Western Electric	....
Approximate quantity made	....	....	~ 30	~ 50	8	1	5	....
Dwg. no. or type	Part of D-150315 or D-150463	RL 11021	....	RL 12499	RL T-D6386	RL 14516	BTL B-470670	....
Crystal no	2	2	3	2	2	4	2	2
Fundamental frequency, Mc/sec	1.4	10	10	26	10	$17\frac{1}{2}$	6.5	10
Diameter, in	About $\frac{7}{8}$ square	1	$1\frac{1}{16}$	$\frac{3}{4}$	$\frac{3}{4}$	$\frac{1}{2}$	1	....
Diameter of active part, in.	About $\frac{7}{8}$ square	$\frac{7}{8}$	0.86	$\frac{5}{8}$	$\frac{5}{8}$	$\frac{3}{8}$	0.885	....
Capacitance at crystal, $\mu\mu$f.	Sender, 55 ± 10; receiver 75 ± 10	~ 60	~ 60	80–93	38 (58 for variable)	30	45	....
Crystal backing	Brass	Mercury	Mercury	Dry steel	Dry steel	Dry steel	Dry steel	....
Line delay, μ sec	2 to 240	6 to 1400	555	586	3000	1000	5000	2000
Length over-all	$21\frac{1}{2}$ in.	7 ft	3 ft	3 ft	$8\frac{1}{2}$ ft	$1\frac{1}{2}$ ft	70 in.	....
Weight (empty) lb	....	24	5	20	140	30	100	
Weight (full), lb	....	....	13	32	200	39	200	

TABLE 7·1.—TABLE OF DELAY-LINE INFORMATION.—(*Continued*)

	Designation of delay line							
	Shockley line	Line *A*	Line *B*	Line *C*	Line *D*	Line *E*	Line *F*	Water line (RAE)
Purpose	Trigger delay		Cancellation with MTI					
Tube material	Steel and insulation	Copper	....	Stainless steel	Stainless steel	Hot-rolled steel	18-8 stainless steel	....
Transmitting medium.	Water and Ethylene glycol	Water	Mercury	Mercury	Mercury	Mercury	Mercury	Water
Tube ID, in.	$2\frac{3}{16}$	....	0.86	$\frac{5}{8}$	$\frac{5}{8}$	$\frac{3}{8}$	0.885	....
Number of sections	1	1	1	1	2	6	4	....
Number of 45° reflection	0	0	1	0	2	8	6	....
Variable feature	Calibrated screw	Manual screw adj.	Movable reflector	Steel bellows	Packing gland	None	Adjustment for alignment	Trombone construction
General thermal regulation.	$135° \pm \frac{1}{2}°F$	None	None	None	Thermally lagged	Thermally lagged	None	$72\frac{1}{2}° \pm 1°C$
Driving frequency	Video	Video	10 Mc/sec	30 Mc/sec	10 Mc/sec	15 Mc/sec	5 Mc/sec	10 Mc/sec
Photograph of assembled line	....	....	Fig. 7·21	Fig. 7·22	Fig. 7·23	Fig. 7·14	....	....

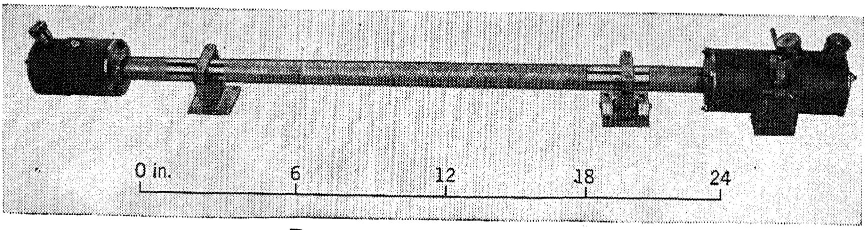


FIG. 7·21.—Line *B*, assembled.

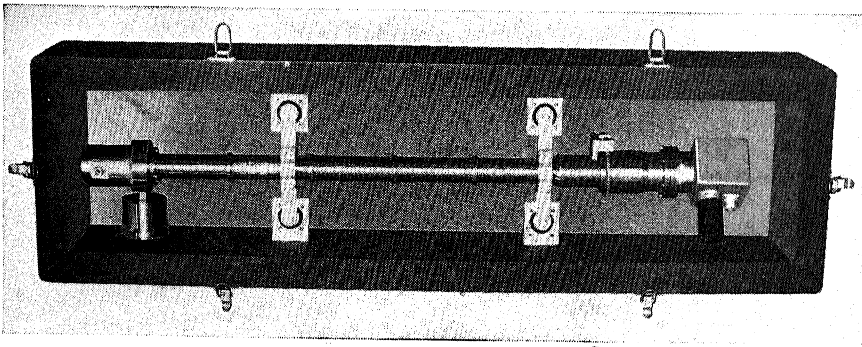


FIG. 7·22.—Line *C*, assembled.

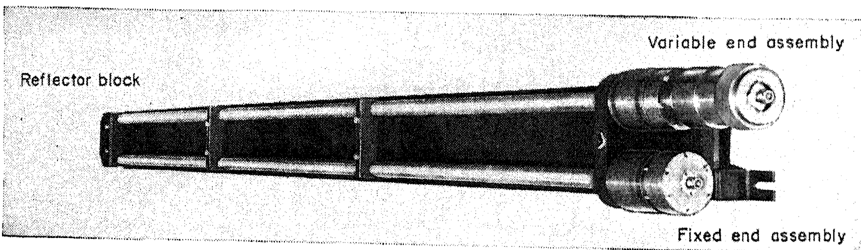


FIG. 7·23.—Line *D*, assembled.

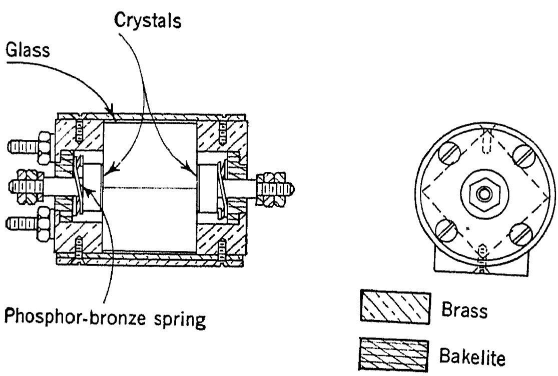


FIG. 7·24.—Glass 6-μsec delay line.

CHAPTER 8

POTENTIOMETERS[1]

BY F. E. DOLE

A potentiometer, as the term is used in this chapter, is an electromechanical device containing a resistance element that is contacted by a movable slider. Such units may conveniently be divided into three classes. Laboratory precision potentiometers are large enclosed units which are chiefly used for low-voltage highly accurate d-c potential measurements in low-impedance circuits. Radio potentiometers (usually called "pots") are small inexpensive units of comparatively poor accuracy which are commonly used for volume control and similar purposes in radio sets and other electronic equipment. The third and more recently developed class, which may be called "commercial precision" potentiometers, is intermediate in character between the first two classes, and will form the subject matter of this chapter.

Commercial precision potentiometers were orginally developed as components of bridges and other test equipment that required variable resistors of good stability and of accuracies of the order of one part in several hundred. The war-born demand for large quantities of electronic measuring equipment—not only for test equipment, but for accurate measurements in radar and sonar—fathered a demand for great numbers of such potentiometers, and the Radiation Laboratory began a development and small-scale manufacturing program that continued until the end of the laboratory's activities. This chapter will be concerned principally with the units developed by the Laboratory or under its sponsorship. Such units were used extensively for data transmission, for electromechanical computing elements, and for medium-precision voltage measurements in radar and other electronic devices.

8·1. The Resistance Element—The heart of a potentiometer is its resistance element, which is always wire-wound in potentiometers of the precision type. The element consists of resistance wire wound on a form or mandrel whose nature depends upon the design of the particular unit. The mandrel is usually a card or strip of sheet insulating material, or a round rod of insulating material or of Formvar-insulated copper wire. The accuracy of the potentiometer depends directly upon the accuracy

[1] An abridgment of this chapter has been published: L. A. Nettleton and F. E. Dole, "Potentiometers," *Rev. Sci. Instruments*, **17**, 356–363 (October 1946).

of the mandrel, which must be made to accurate dimensions and accurately wound. Figure 8·1 shows a number of resistance elements of several forms. Figure 8·1*a* shows a toroidal mandrel; this type is more difficult to wind than the other types, but has the advantage that when it is once properly wound it need not be bent or otherwise distorted in order to mount it in a potentiometer. It is also the only type that is practical when a useful angle of 360° is required. The long narrow card of Fig. 8·1*b* is used in most linear potentiometers and the square card of Fig. 8·1*c* is used in most sine-cosine units. The "violin string" winding of Fig. 8·1*d* is used in linear potentiometers, both in the single-turn type such as the RL-270 series and in the multiturn units such as the Beckman Helipot and the Gibbs Micropot. Nonlinear potentiometers, except sine-cosine units, are usually based upon a tapered form of the card of Fig. 8·1*b*; an example is the logarithmic 433AC potentiometer used in the General Radio 650A bridge.

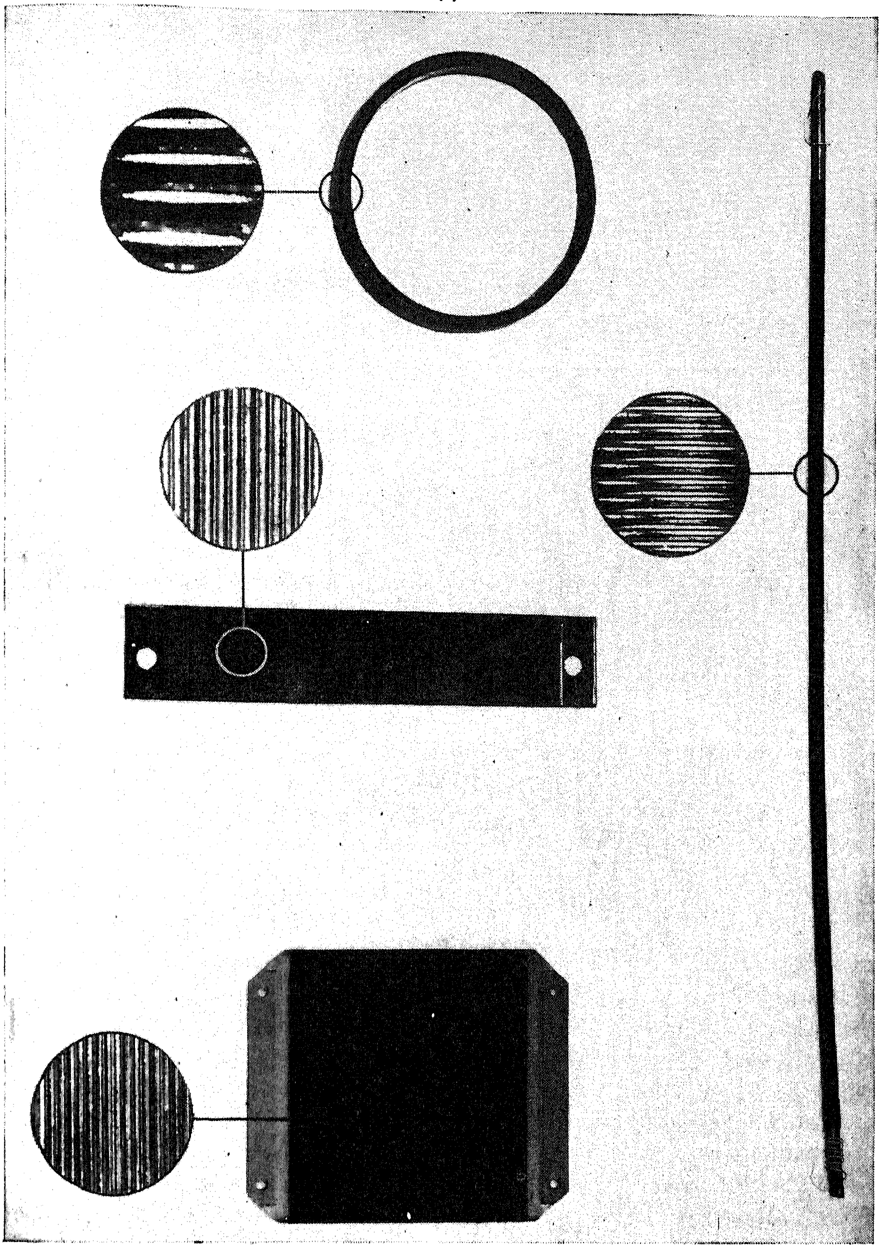
Violin-string or Kohlrausch windings are usually wound on a core of Formvar-insulated copper wire. Such a mandrel has the advantage that it is uniform in dimensions, smooth and free from surface defects, easily formed into the shape required for mounting in the potentiometer, and of excellent heat conductivity so that the winding can dissipate more power than with most other constructions. Its principal disadvantage is the excessive capacitance between the turns of the winding and the copper core, which limits the frequency range at which such an element can be used. Extruded rods of a suitable plastic may be used instead of the copper core, but it is difficult to obtain rods of sufficient dimensional stability and uniformity.

Laminated sheet phenolic plastics have been used almost universally for card-type mandrels. They have been satisfactory in most cases, and much of the trouble that has occurred has proved to be due to improper design or fabrication of the mandrel rather than to the material itself. The susceptibility of sheet phenolics to water absorption has not been a serious defect since the impedance level at which a wire-wound potentiometer is operated is seldom excessively high, and since the whole element must be properly varnished after winding in order to keep the turns in place while buffing the contact area and during operation. If operation in tropical climates is to be expected a suitable fungicide should be mixed with the varnish.

Fiberglas cloth laminated with nonwater-absorbent resins is superior to phenolics from the standpoint of stability of dimensions, water absorption, and resistance to fungus attack, but has not been much used for mandrels because it is difficult to machine. The abrasive character of the glass particles necessitates the use of Carboloy tools for all cutting operations and even then tool life is poor. Glass-cloth laminates are good for insulating and protecting sheets.

(a)

(b)

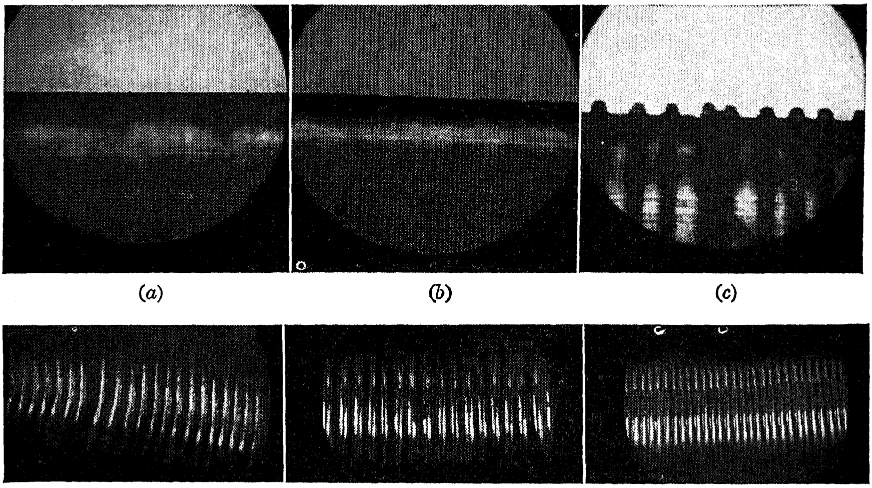


(d)

(c)

FIG. 8·1.—Potentiometer resistance elements. (a) Toroidal element; (b) rectangular card; (c) square card; (d) "violin string," Kohlrausch, or circular mandrel. The small circles are microphotographs of portions of the windings.

It is essential that the surface of the mandrel be free from nicks, dents, and abrasions, especially beneath the path of the contact. Wire mandrels may be drawn through a diamond die after coating; this straightens, sizes, and smooths the mandrel in a single operation. Card-type mandrels should have the edges rounded to a semicircular shape by means of a special milling cutter. This cutter must be kept very sharp and the cards should be inspected after the milling operation to make sure that the milled surface is smooth and free from waves or tool marks. It is usually desirable to buff the milled surface, using a soft or medium felt buff with aluminum oxide or Tripoli 2D as an abrasive. Mandrel dimensions should be held to well within the required tolerance, especially



(a) (b) (c)

(d) (e) (f)

FIG. 8·2.—Mandrel and winding defects: (a) Card-type mandrel properly milled; (b) rough mandrel; (c) and (d) irregular windings due to rough mandrels; (e) widely spaced winding; (f) good winding on properly treated mandrel.

if the total resistance tolerance is small. A rough surface on the mandrel will cause displacement of the wire during the winding process. Such a displacement will result in low and high wires or nonuniform spacing and will seriously affect accuracy. Figure 8·2 shows microphotographs of satisfactory and unsatisfactory mandrels and windings.

The Resistance Wire.—The resistance wires used for potentiometers are usually drawn from alloys of the "Nichrome" family or from copper-nickel alloys similar to Midohm or Lohm. A discussion of the properties of such alloys has been given in Chap. 3 of this volume; Table 8·1 gives the resistance in ohms per foot of a number of the more common resistance alloys, in sizes from No. 10 AWG to 0.60 mil in diameter.

The accuracy and uniformity requirements for resistance wire that is to be used in potentiometer elements are much more stringent than those

TABLE 8·1.—COMMERCIAL RESISTANCE WIRE CHARACTERISTICS

			Trade names					
			Chromel C Nichrome Tophet C Alloy C	Chromel A Nichrome V Tophet A Alloy A	Copel Advance Cupron Alloy 45	Midohm 180 Alloy	90 Alloy	Commercial copper wire
Nominal composition, per cent			60 Ni 16 Cr 24 Fe	80 Ni 20 Cr	45 Ni 55 Cu	22 Ni 78 Cu	12 Ni 88 Cu	99.9 Cu
Ohms/circular mil foot			675	650	294	180	90	10.5
Temp. coefficient/°C			0.00022	0.00014	0.00002	0.00016	0.00038	0.00400
AWG No.	Diam., mils	Circular mils	Ohms per foot at 20°C					
10	102	10,400	0.0649	0.0625	0.0283	0.0173	0.0087	0.00100
11	91	8230	0.0815	0.0785	0.0355	0.0217	0.0109	0.00126
12	81	6530	0.103	0.0991	0.0448	0.0274	0.0137	0.00159
13	72	5180	0.130	0.126	0.0567	0.0347	0.0173	0.00200
14	64	4110	0.165	0.159	0.0718	0.0439	0.0219	0.00252
15	57	3260	0.208	0.200	0.0905	0.0554	0.0277	0.00318
16	51	2580	0.260	0.250	0.113	0.0692	0.0346	0.00402
17	45	2050	0.333	0.321	0.145	0.0888	0.0444	0.00506
18	40	1620	0.422	0.406	0.184	0.112	0.0562	0.00638
19	36	1290	0.521	0.502	0.227	0.139	0.0694	0.00805
20	32	1020	0.659	0.635	0.287	0.176	0.0879	0.0102
21	28.5	810	0.831	0.800	0.362	0.222	0.111	0.0128
22	25.3	642	1.06	1.02	0.456	0.281	0.141	0.0161
23	22.6	509	1.32	1.27	0.576	0.352	0.176	0.0204
24	20.1	404	1.67	1.61	0.728	0.446	0.223	0.0257
25	17.9	320	2.11	2.03	0.918	0.562	0.281	0.0324
26	15.9	254	2.67	2.57	1.16	0.712	0.356	0.0408
27	14.2	202	3.35	3.23	1.46	0.893	0.446	0.0515
28	12.6	160	4.25	4.09	1.85	1.13	0.567	0.0649
29	11.3	127	5.29	5.09	2.30	1.41	0.705	0.0818
30	10.0	101	6.75	6.50	2.94	1.80	0.900	0.103
31	8.9	79.7	8.52	8.21	3.72	2.27	1.14	0.130
32	8.0	63.2	10.6	10.2	4.59	2.81	1.41	0.164
33	7.1	50.1	13.4	12.9	5.83	3.57	1.78	0.207
34	6.3	39.8	17.0	16.4	7.41	4.54	2.27	0.261
35	5.6	31.5	21.5	20.7	9.38	5.74	2.87	0.329
36	5.0	25.0	27.0	26.0	11.8	7.20	3.60	0.415
37	4.5	19.8	33.3	32.1	14.5	8.89	4.44	0.523
38	4.0	15.7	42.2	40.6	18.4	11.2	5.62	0.660
39	3.5	12.5	55.1	53.1	24.0	14.7	7.41	0.832
40	3.1	9.9	70.2	67.6	30.6	18.7	9.36	1.05
..	2.75	7.6	88.7	85.5	38.7	23.8	11.9	1.39
..	2.50	6.2	108	104	46.7	28.8	14.4	1.68
..	2.25	5.1	133	128	57.6	35.5	17.8	2.07
..	2.00	4.0	169	162	73.5	45.0	22.5	2.62
..	1.75	3.1	221	212	95.0	58.7	29.4	3.43
..	1.50	2.2	300	289	131	80.0	40.0	4.66
..	1.40	2.0	344	331	150	91.8	45.9	5.35
..	1.30	1.7	399	385	174	106	52.2	6.21
..	1.20	1.4	469	451	204	125	62.5	7.29
..	1.10	1.2	558	537	243	149	74.3	8.68
..	1.00	1.0	675	650	294	180	90.0	10.5
..	0.90	0.81	833	802	363	222	111	13.0
..	0.80	0.64	1054	1016	459	281	141	16.4
..	0.70	0.49	1378	1327	600	367	184	21.4
..	0.60	0.36	1874	1806	817	500	250	29.2

together to prevent twisting of the card, and the tailstock was spring-loaded to ensure a constant tension on the card. Special jaws for each size of card were provided for the chucks, and a smooth and accurate speed control was incorporated in the drive. Cards up to $7\frac{1}{2}$ by 20 in. could be handled.

With the development of the RL270 series of potentiometers, which use a round mandrel of heavy Formvar wire, a new winding machine was built by modifying an inexpensive screw-cutting lathe. This machine is shown in Figs. 8·7 and 8·8. The modifications included the substitution of precision cut gears for the original die-cast change gears, a simple wire-tensioning and feed device on the carriage, and a ball-bearing tailstock

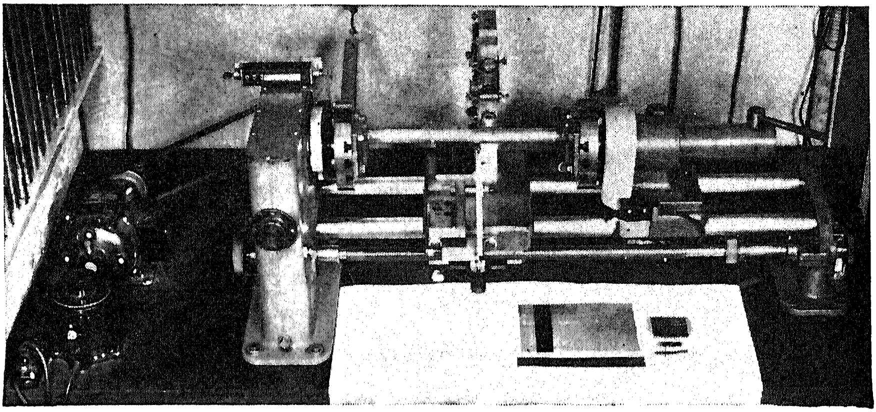


FIG. 8·5.—Flat-card winding machine.

chuck. Round mandrels can be wound at a much higher winding speed than is possible with flat cards since the wire velocity is uniform. This machine proved very satisfactory in winding resistance elements with linearities of ± 0.03 per cent in the 100,000-ohm value to ± 0.15 per cent in the 200-ohm value.

A machine for winding toroidal elements such as that shown in Fig. 8·1*a* was designed, but construction had not yet started at the time the activities of the Laboratory were terminated. The design incorporated a number of novel features, including a preset turn counter and a precision speed control which would greatly facilitate the production of windings of identical characteristics.

Varnishing, Curing, and Buffing.—After winding, the resistance element must be coated with a suitable varnish in order to hold the wires in place and to protect them against moisture and mechanical abuse. One difficulty that arises with most electrical impregnating varnishes is a creeping or displacement of the wires during the curing process. After a number of trials a satisfactory process was evolved. A single coat of

for magnet wire, for instance. For reproducibility and accuracy not only must the composition and heat treatment of the wire be accurately controlled, but the wire diameter and the thickness of the insulation must be held within close limits. Wire that has been coated with Formvar or Formex by the extrusion process has been found to be greatly superior to ordinary enameled wire, not only because of its more uniform over-all diameter but also because it is free from "beady" spots and similar defects. Figures 8·3 and 8·4 show microphotographs of defective wire and of windings made from it.

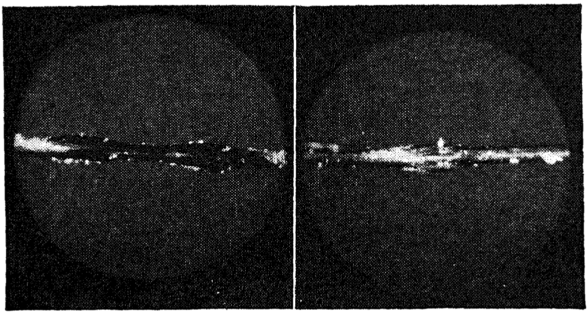


FIG. 8·3.—Defective wire.

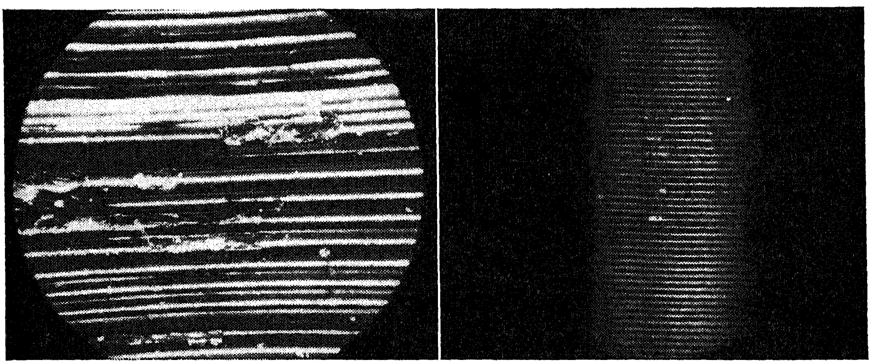


FIG. 8·4.—Defective windings due to bad wire.

The Winding Process.—Windings of sufficient accuracy for use in precision potentiometers can only be made on properly designed winding machines, and several such machines were designed and built at the Radiation Laboratory. Figure 8·5 is a photograph of a machine that proved very satisfactory for winding flat card-type resistance elements, and Fig. 8·6 is a close-up of the carriage showing the wire-straightening pulleys and the dust brushes. The machine was designed to minimize backlash and periodic errors due to the feed gearing, to ensure smooth and uniform motion of the carriage, and to furnish accurate control of the wire tension. The headstock and tailstock chucks were driven

TUF-ON No. 74-F or No. 76-F varnish (made by the Brooklyn Varnish Company) diluted with about 40 per cent of the appropriate solvent was applied by spraying, brushing, or dipping. Both varnishes are of the

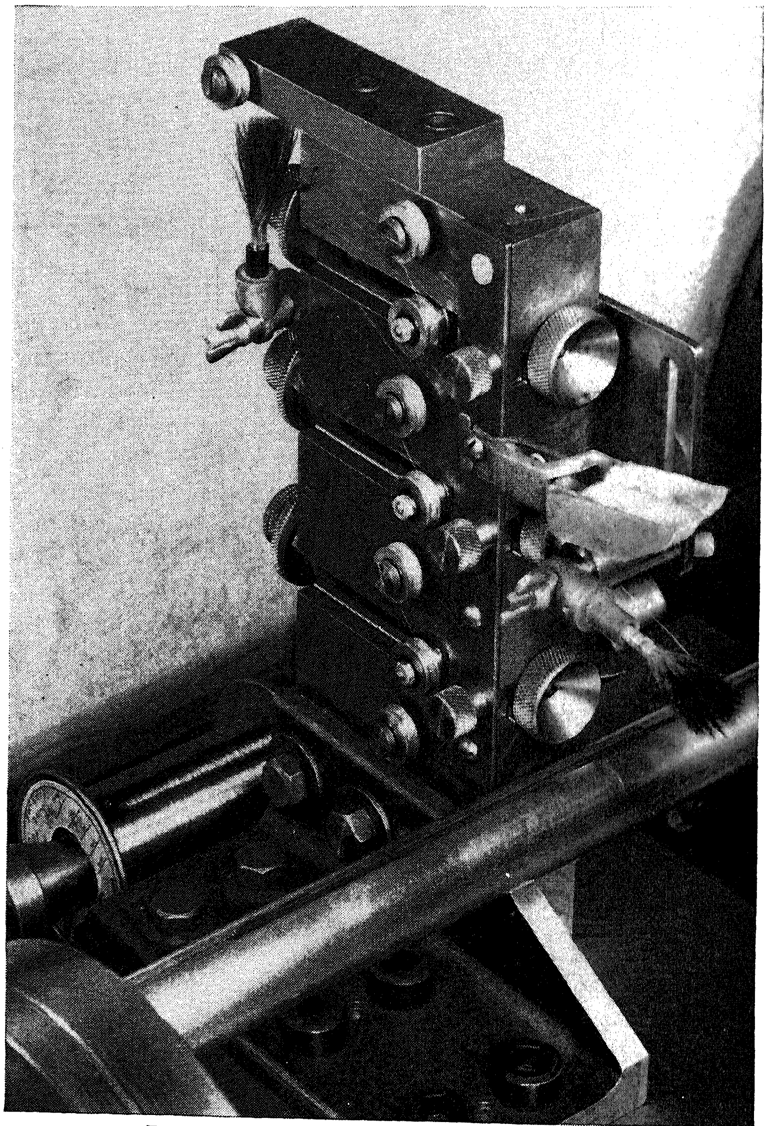


FIG. 8·6.—Carriage of flat-card winding machine.

phenolic resin type, both contain a fungicide, and will air-dry within 48 hr. Drying may be speeded up by heating to approximately 50°C in a convection oven. If the specific gravity of the varnish is maintained

at the proper value the coating will be ready for buffing after 24 hr in the oven.

Two methods of buffing were standardized at the Radiation Laboratory. For both, wheels of white "Extra-Spanish" felt in the medium or

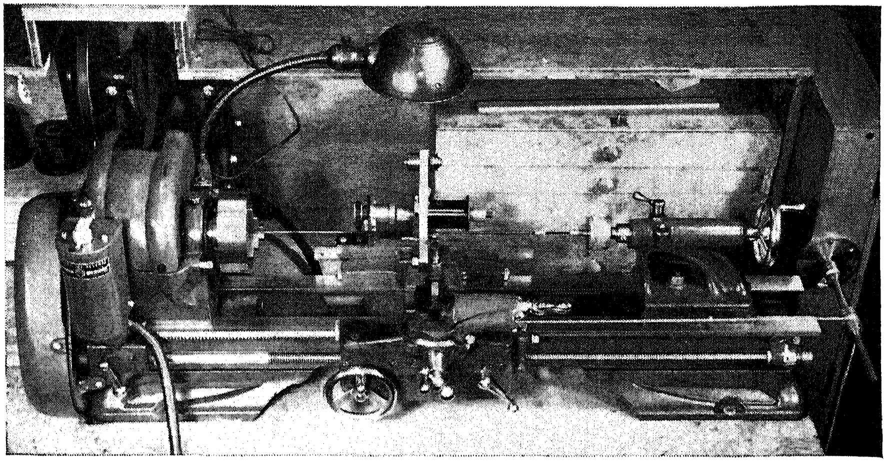


FIG. 8·7.—Round-mandrel winding lathe, front view.

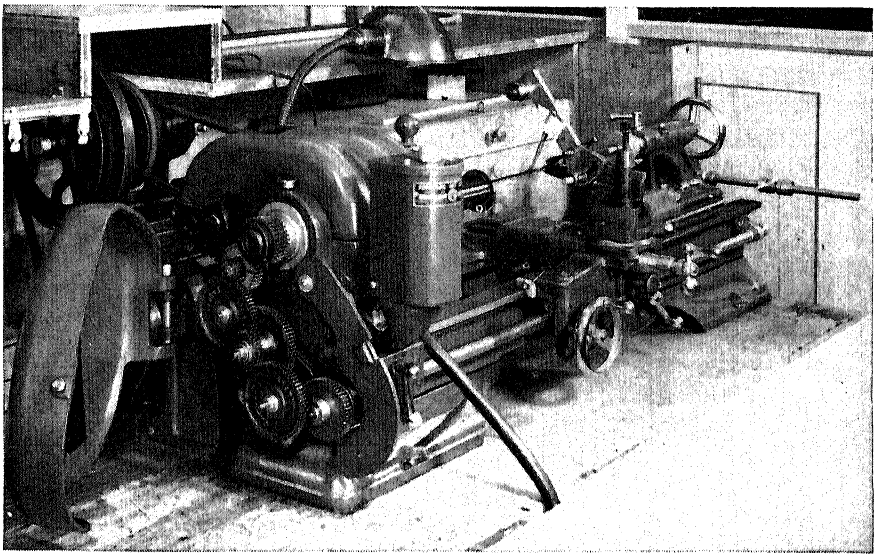


FIG. 8·8.—Round-mandrel winding lathe, side view.

soft grades were used. For buffing mandrels and for windings of conventional enameled wire the wheels were run at about 2500 ft/min and aluminum oxide or "Tripoli 2D" were used as abrasives. For buffing windings of Formex-insulated wire and for all "violin string" windings

the wheels were run at 1500 ft/min and were used without abrasive. Buffing of windings must be done with great care in order not to remove metal from the wire or to heat the winding excessively. This is particularly important with round mandrels.

To sum up, the production of resistance elements of high accuracy and stability demands attention to the following points:

1. Proper preparation of the mandrel.
2. The use of wire of the highest quality.
3. Winding on a properly designed and accurate winding machine, run by a careful and competent operator.
4. Care in removing the winding from the machine, and in handling through all stages of production.
5. Impregnation with a suitable varnish, maintained at the correct specific gravity.
6. Adequate curing at the correct temperature.
7. Careful buffing, using the correct technique.
8. Proper assembly technique.
9. Adequate inspection.
10. Cleanliness throughout the entire operation.

Resistance elements manufactured with these precautions will remain stable and accurate throughout the life of the potentiometer.

8·2. Mountings and Enclosures.—The mountings and enclosures of potentiometers may take various forms; the illustrations of this chapter show a number of typical examples. Most commercial precision potentiometers are cylindrical in shape, ranging in axial length from $\frac{3}{4}$ to 3 in. and in diameter from $1\frac{1}{2}$ to 5 in. Enclosed types are usually provided with a locating boss or ring and with a mounting flange with slots for phasing.

The design of the body of the potentiometer depends upon the way in which the resistance element is to be mounted, and there is a choice of three methods for accomplishing this. In one, the element, which has been wound while it is straight, is wrapped around a cylindrical form that is provided with an axial shaft. The form may be stationary and provided with a mounting surface, and with central bearings for the shaft, or it may be fastened to, and rotate with, the shaft. The resistance element may be drawn around the form by an assembly jig or fixture, or it may be held in place by a permanent protective strap. In either case it is fastened by screws or rivets through the wall of the form.

A second method employs a toroidal form such as that of Fig. 8·1a, which is pressed onto a central cylindrical body similar to that used in the previous method. An enclosure usually surrounds the element and central body in this type of construction.

In the third method the resistance element is mounted on the inside of a hollow cylindrical form. In units having a violin-string winding, such as the RL-270 series, the element may be held in grooves in two insulating pieces that expose a portion of the inner surface of the winding. In card-type units the card may be bent around a temporary arbor, pressed into the cylindrical body, and the ends fastened with rivets, screws, or pins. The element may also be held in a temporary fixture while the body is molded around it; this type of construction is often used in multiturn units such as the Micropot.

The potentiometer body itself may be made either of metal or of insulating material. If made of the latter it may be molded and used as it comes from the mold, or it may be finish-machined after molding. With most plastics finish-machining removes the comparatively impervious skin of the molding and may increase any tendency to water absorption. This can be counteracted to some extent by suitable sealing treatments, but it is preferable to disturb the surface as little as possible. If finish-machining is not to be used it is necessary to choose a plastic with the greatest possible dimensional stability and to take great care both with the mold design and with the curing process to maintain sufficiently accurate dimensions in the molded piece.

For units of high precision, metal is much superior to plastics from the standpoint of dimensional stability. Aluminum alloys are frequently used; one casting alloy that has good stability is Alcoa 395 with a T-6 heat treatment. The principal disadvantage of using metal is the necessity of providing additional insulation for the winding. Bodies may also be machined from rod or plate stock, either of metal or of insulating material. For the RL-270 series the bodies were machined from a glass-mat-filled plastic known as Formica MF-66. This material proved to be very stable dimensionally and to be unaffected by tropical climates. Certain molded plastics with mineral fillers were also satisfactory.

In the cheapest types of commercial precision potentiometers the shaft rotates in a cored or reamed hole in the molded body. This is satisfactory for a low-precision unit that is to be adjusted manually, but the variation in hole diameter and position renders the method unsuitable for high precision or for gear-driven units. Brass, bronze, or Oilite inserts may be molded into the body, and will improve the centering of the shaft and decrease the bearing friction. Where highest precision and minimum friction are required it is necessary to use ball bearings.

Shafts may be of either metal or plastic material. The latter is often used in the cheaper potentiometers, but is unsatisfactory in many applications because of its tendency to warp and its great flexibility compared to metals. If an insulating shaft is required one useful expedient is to press a thin-walled plastic tube over a steel shaft, the

latter being knurled if necessary to prevent slipping. It is preferable, however, to put the insulation in the hub of the contact arm where it belongs and to use a grounded metal shaft. Metal shafts are usually of steel; drill rod is convenient but stainless steel is to be preferred if there is any possibility of corrosion in service. Hubs, collars, etc., may be secured to the shaft by setscrews, preferably in pairs at 90°, but pinning or clamping is better. Split hubs with clamp screws are particularly handy from the standpoint of ease of adjustment.

Potentiometers intended for laboratory use or for mounting within adequately sealed cabinets are not usually enclosed. Units intended for operation in exposed positions or in the tropics must be provided with adequate enclosures. These units cannot be hermetically sealed without using an expensive and clumsy hermetic shaft seal, but the use of waterproof AN connectors for the terminals, suitable gasketing, and a compression shaft seal such as a Garlock Klozure will afford adequate protection for all but the most extreme conditions. Under most conditions ordinary dusttight construction will suffice. Typical potentiometer enclosures are shown in the potentiometer drawings of this chapter.

8·3. Leads and Attachments.—One rather troublesome problem in the construction of a potentiometer is the provision of sturdy and permanent attachments to the resistance winding. The use of very small wire sizes and of nickel-chromium alloy wire that cannot be satisfactorily soft-soldered makes such connections difficult.

Connections to the resistance element may depend upon mechanical pressure alone, or they may be soldered. Pressure connections may be made in several ways. A screw or a stud may be used to draw a piece of metal tightly against a cleaned portion of the winding, or the wire may be pressed between two pieces of metal. The screw may then be used as a binding post. A rivet may be used instead of the screw; a soldering lug may also be used under the head of the rivet. A rod tipped with a soft noble metal such as gold may be pressed against a bared spot on the winding, as in the RL-270 series units. A connection may be made to Nichrome wire by placing the cleaned wire across a strip of copper foil and persuading molten solder on the copper strip to cover the wire as well. Although this is not a true soldered joint the contraction of the solder on cooling helps to lock the wire tightly in place. The finished joint should be inspected carefully and tested for electrical continuity. This method is sometimes useful for making taps on flat cards.

Successful soft-soldered joints may be made to nearly all resistance alloys except those of the Nichrome family. Rosin or rosin in alcohol is the only permissible flux, in spite of advertising claims to the contrary. The flux should be used sparingly to avoid later trouble with excessive residue, and the joint should be cleaned with alcohol if possible.

Breakage of the smaller wires during the soldering process can often be avoided by the use of a small strip of copper or brass foil as an intermediate connection. The foil and the wire are tinned and soldered together and the other end of the foil is then soldered to the terminal. Alternatively, a pressure connection can be made from the foil to the terminal. The end of the foil may be captured beneath a washer held by the terminal stud or rivet, or may be inserted into the end of a metal tube or hollow rivet moulded into the frame, and the end of the tube crushed onto the foil.

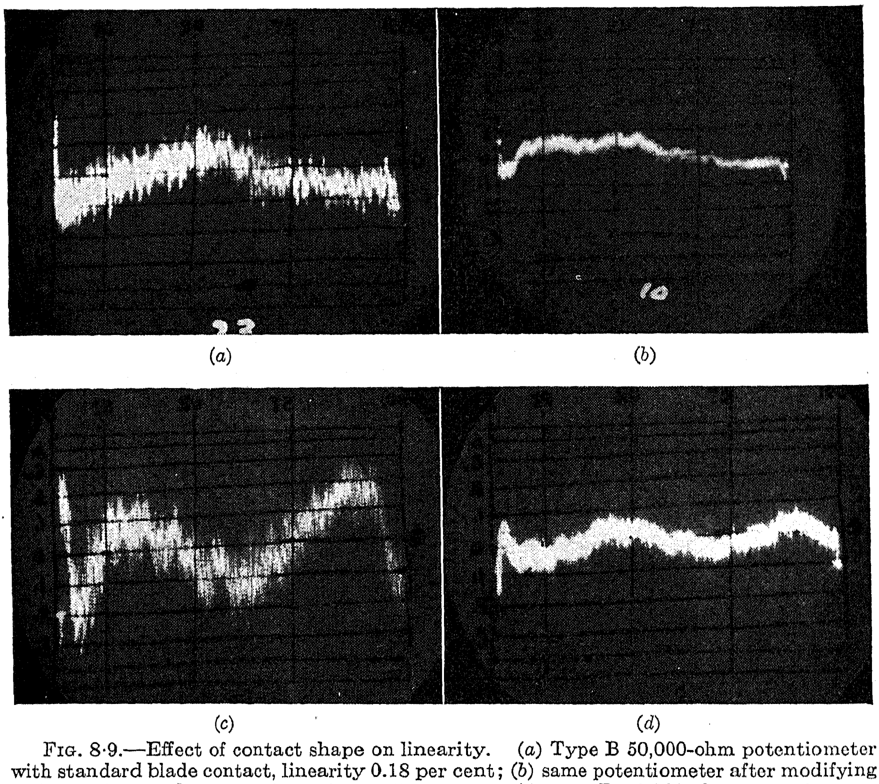
One method that is occasionally used involves baring and tinning a spot on the winding, opposite and close to a rivet or insert in the housing. A drop of solder on the tip of the rivet will form a conducting bridge when the latter is heated. Since the lug for the connection to the external lead is usually located at the outer end of the rivet there is always the possibility that the heat of soldering the external lead may destroy the solder bridge.

Nickel-chromium alloys cannot be successfully soft-soldered but must be hard-soldered or welded. No successful welding techniques were tried at the Radiation Laboratory, but one convenient method of hard-soldering fine wires was developed. A loop of bare No. 12 or No. 14 copper wire 5 or 6 in. long was looped between the terminals of a 50-amp 1.25-volt transformer connected to a 5-amp Variac and a foot switch. Copper is the only material suitable for the loop since with materials of lower conductivity the drop of solder will freeze as soon as it bridges an appreciable length of the loop. The center of the loop was painted with borax flux and sufficient current was passed through it to melt hard solder. It is easy to pass the joint that is to be soldered through the drop of molten solder in the loop. The solder rapidly dissolves the copper wire and both loop and solder drop must be replaced after a short time. The fine wires should be passed through the drop rapidly and at right angles to the direction of the current flow in order to minimize the chances of dissolving or burning them out.

8·4. Contacts.—The accuracy and life of a potentiometer depend primarily upon the design and material of the movable contact. Much of the work of the potentiometer group at the Radiation Laboratory was devoted to the investigation of this problem and a very extensive series of life tests was carried out.[1] These tests showed that for windings of nickel-chromium-alloy wire there is one outstanding alloy, Paliney No. 7, made by the J. M. Ney Company of Hartford, Conn. It is a palladium-silver alloy with additions of platinum, gold, copper, and zinc. Tests on

[1] F. E. Dole and R. J. Sullivan, "Life Test of Contact Material on Standard Linear Wire-wound Potentiometers," RL Report No. 617, Mar. 12, 1946; R. J. Sullivan, "The RL270 Series of Precision Potentiometers," RL Report No. 864, Mar. 25, 1946.

windings of copper-nickel alloys were not completed but indicated that for these materials the best contact material was No. 19 Alloy, an alloy of platinum and silver made by the H. A. Wilson Company of Newark, N. J. Stellite and various grades of carbon were also used in some of the earlier potentiometers designed by the Laboratory, but were definitely inferior to the Paliney and No. 19 Alloy. Over thirty alloys were tested altogether, and the spring-temper phosphor bronze commonly used for potentiometer contact arms was found to be one of the poorest for the purpose. Typical linearity test oscillograms and microphotographs of contacts and windings after the tests are shown in Figs. 8·9 through 8·14.



(a) (b)

(c) (d)

FIG. 8·9.—Effect of contact shape on linearity. (a) Type B 50,000-ohm potentiometer with standard blade contact, linearity 0.18 per cent; (b) same potentiometer after modifying with 0.020-in. rod contact, linearity 0.05 per cent; (c) type D 50,000-ohm potentiometer with finger-type arm, linearity 0.32 per cent; (d) same potentiometer after modifying with rod contact soldered to fingers and cut between each pair of fingers, linearity 0.12 per cent.

A number of different shapes and sizes of contacts may be used on standard wire-wound mandrels where the surface of the wire will not be smoothed down to a flat surface. A cylindrical rod with its axis parallel to that of the wire has proven very satisfactory, one reason being that with such a shape no more than two wires can be contacted at the same

time so that no more than one turn can be short-circuited by the contact. The superiority of such a contact design is shown by Fig. 8·9. In this figure *a* and *b* are linearity oscillograms of a 3-in. potentiometer similar to the General Radio Company Type 314, with the standard phosphor-bronze contact arm as furnished by the manufacturer, and with an arm with a cylindrical Paliney No. 7 contact. Figures 8·9*c* and *d* are a similar pair applying to a 5-in. RL-255. In each case the improvement due to the better contact is evident.

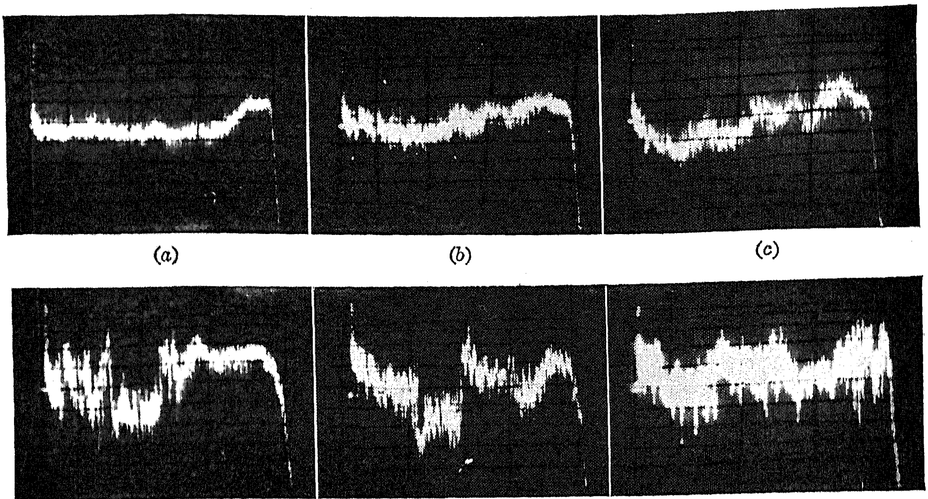


FIG. 8·10.—Linearity test of 3-in. 50,000-ohm potentiometer. (*a*) As delivered; brush pressure approximately 70 g; linearity 0.17 per cent; (*b*) taken at 10,000 cycles; linearity 0.22 per cent; (*c*) taken at 66,000 cycles; linearity 0.22 per cent; (*d*) taken at 202,000 cycles; linearity 0.32 per cent; (*e*) taken at 500,000 cycles; linearity 0.35 per cent; (*f*) taken at 1,002,800 cycles; linearity 0.28 per cent plus noise; brush pressure, 55 g, contact worn 0.0085 in. deep, area $\frac{7}{64}$ by $\frac{1}{16}$ in.

This gain in linearity was found in every case in which a small cylindrical contact was substituted for a larger one of flat or indeterminate shape. For one sample group of twenty 3-in. units, for example, the improvement in linearity was about 0.03 per cent, or about one third of the mean deviation from linearity of the unmodified units.

The improvement in initial linearity is entirely due to the improved contact shape and size, but the use of a contact of small radius involves high unit pressures at the point of contact, and wear becomes prohibitive unless the right contact material is used for the particular resistance alloy. For potentiometers whose windings have been buffed only enough to remove the varnish and wire enamel, leaving the wires round, a cylindrical contact with a diameter of 0.020 to 0.040 in. is a suitable size for most windings. For small closely spaced wires a smaller radius might be better; for large wire and wide spacings a larger radius would

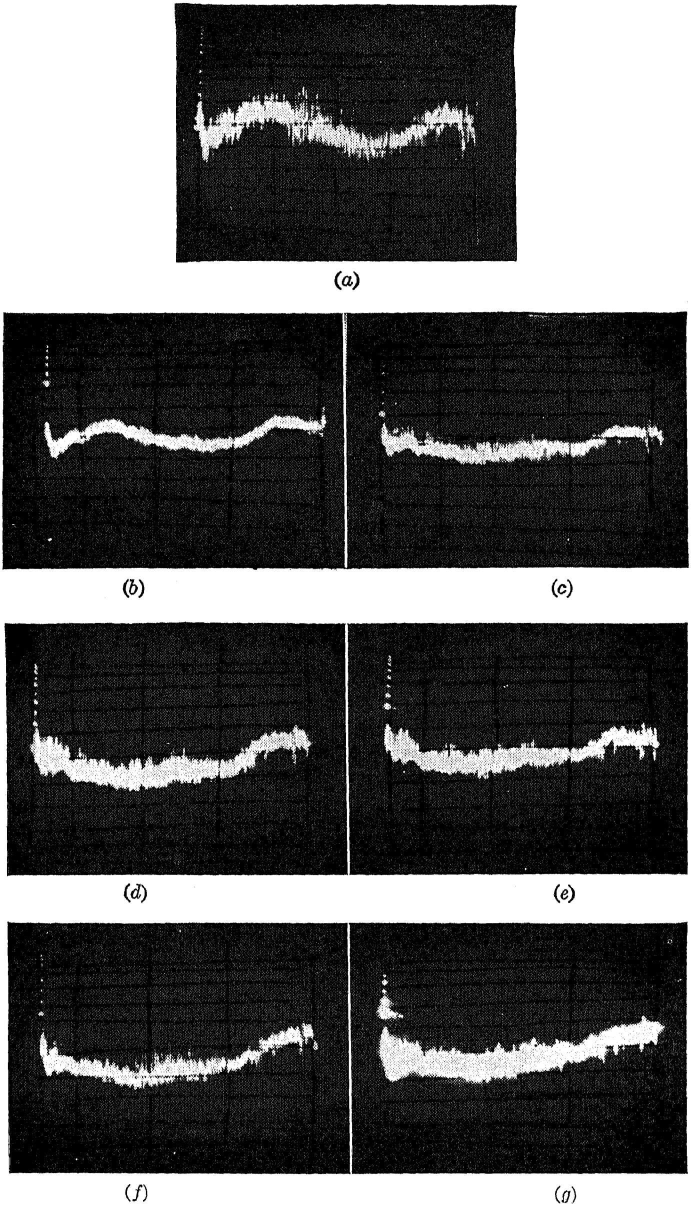
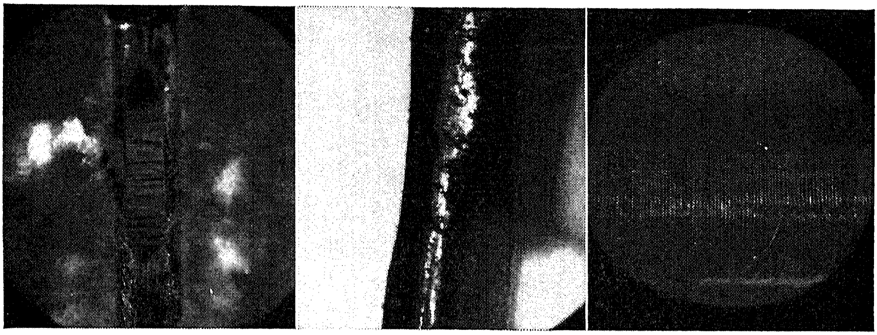


FIG. 8·11.—Linearity test of 3-in. 50,000-ohm potentiometer with Paliney No. 7 contact. (*a*) As received from manufacturer; brush pressure 110 g, no end play; linearity 0.18 per cent; (*b*) potentiometer using Paliney No. 7 contact, 0.040 in. in diameter on regular arm; brush pressure 50 to 65 g; linearity 0.08 per cent; (*c*) taken at 10,000 cycles; linearity 0.10 per cent; (*d*) taken at 66,000 cycles; linearity 0.12 per cent; (*e*) taken at 202,000 cycles; linearity 0.12 per cent; (*f*) taken at 500,000 cycles; linearity 0.13 per cent; (*g*) taken at 1,002,800 cycles; linearity 0.10 per cent; brush pressure 45 g; contact wear 0.0015 in.

be required. One possibility of decreasing wear on the winding would be to use a rolling rather than a sliding contact, but one such unit that was tested proved unsuccessful. Its contact was in the form of a blunt double cone that wedged between the edge of the winding and a central contact disk. The initial linearity of 0.24 per cent increased to 0.36 per cent and very bad noise developed after only 6125 cycles. This performance may be compared with that of a standard 3-in. potentiometer, which is shown in Fig. 8·10, and that of a similar unit modified by the substitution of a Paliney contact, shown in Fig. 8·11. It can be seen from these pictures that the deterioration in performance is much more severe with the phosphor-bronze arm. This is presumably due to the fact that the phosphor bronze is worn away much more rapidly than the Paliney, and this fact was demonstrated by other tests in which the



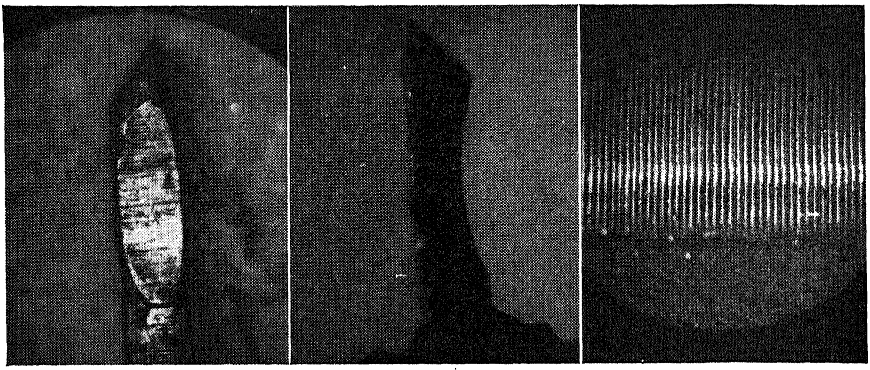
(a) (b) (c)

FIG. 8·12.—Wear of Paliney No. 7 contact and Nichrome wire. (a) Contact surface after 10^6 cycles; (b) contact profile, worn 0.0015 in. deep; (c) winding, very little wear; piece of material in lower center is not a broken wire but a piece of lint. Contact material excellent for Nichrome wire.

replacement of a worn Paliney contact by a new one after 1,000,000 cycles restored the linearity of the potentiometer to its initial value.

In the tests just described the deterioration of the performance was due primarily to wear of the moving contact. If a harder material such as Stellite is used, however, the deterioration is even more rapid because of wear of the wires. It is certainly preferable to have the wear take place on the moving contact because it can be much more easily replaced than the winding. Although several other materials proved fairly satisfactory the performance of Paliney No. 7 was outstanding on windings of nickel-chromium wire. With the softer cupro-nickel alloys, Paliney seems to be too hard and softer contact alloys such as Wilson No. 19 Alloy give longer winding life. The tests on the cupro-nickels were not so complete as those on Nichrome, but it appears that the life of the softer alloy windings should not be greatly inferior if the proper contact material is used. Three sets of microphotographs show-

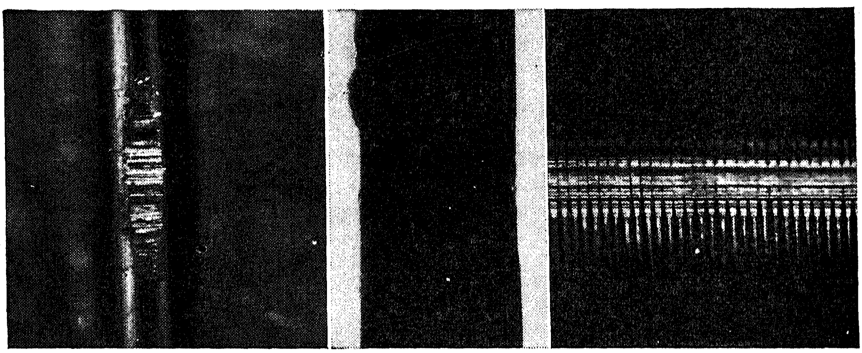
ing windings and contacts after wear tests, are shown in Figs. 8·12 through 8·14. The advantages of matching the contact material to the wire alloy are obvious.



(a) (b) (c)

FIG. 8·13.—Wear of No. 19 Alloy contact and Lohm wire. (a) Contact surface after 875,000 cycles; (b) contact profile worn 0.006 in. deep; (c) winding, very little wear. Contact material excellent for Lohm wire.

The contact paths of certain potentiometers such as the RL-B, RL-225, and RL-200B are honed down so that the contact surfaces are flat rather than convex. Special forms of contacts have been used in



(a) (b) (c)

FIG. 8·14.—Wear of Paliney M contact and Lohm wire. (a) Contact surface after 11,850 cycles; (b) contact profile, worn less than 0.001 in. deep; (c) winding, wires very badly scored and peened, resulting in drop to less than one-third of original resistance.

such cases; some of these special contacts are shown in the drawings of the potentiometers.

It is important to maintain the correct contact pressure throughout the life of the unit, and the contact arm must be designed to accomplish this. Excessive pressure causes unnecessary wear and shortens the life of the unit; insufficient pressure results in noisy operation, particularly under bad vibration conditions or with rapid motion of the contact arm.

For contacts of the types described above the optimum pressure is 40 to 50 g; a potentiometer with this pressure and a properly shaped Paliney contact on Nichrome wire should have a useful life of at least 1,000,000 cycles. Much greater life can be obtained in some cases; one RL-255 unit lasted over 12,000,000 cycles without excessive deterioration. The results of a large number of life tests are given in Radiation Laboratory Reports No. 617 and No. 864.

8·5. Nonlinear Potentiometers.—So far, nothing has been said explicitly concerning the relationship between the shaft angle and the variation of resistance between the contact point and the end of the winding. For many purposes it is desired that this relation be linear, but for certain applications, especially in electromechanical computers and similar devices, it is necessary that some nonlinear function be generated, often to a high degree of accuracy. There are a number of methods of generating such nonlinear functions by means of potentiometers, and this section will list them briefly without attempting to go into great detail.

The choice of a method depends upon two factors; the form of the desired function and the accuracy with which it must be approximated. Strictly speaking, the only type of potentiometer which generates a continuous function is one in which the contact moves along the whole length of the wire. In the usual case, in which the contact touches the bared portion of one turn after another on a wound mandrel, it generates a curve consisting of a series of small steps, the size of the steps depending upon the number of turns in the winding and the applied voltage. For most purposes, however, the steps are small enough and numerous enough so that the resulting curve can be considered smooth. There are many applications in which a small number of steps—say 30 to 100—are sufficient, and in such cases a step potentiometer can be used. This is simply a multipoint switch with resistors connected between each successive pair of points. A familiar example of such a step potentiometer is the volume control commonly employed in broadcast stations. This type of potentiometer is the most flexible in conforming to an arbitrary function, but if the conformation must be close—that is, if high resolving power is required—a prohibitively large number of points and resistors must be used.

A set of straight-line segments is a considerably better approximation to a smooth curve than a set of steps, and there are several potentiometer constructions that result in such a function. One such is the use of a stepped mandrel; since the slope of the curve is proportional to the width of the mandrel a series of steps on the mandrel will result in a curve consisting of a series of linear segments of different slopes. Alternatively, the wire size can be varied; the greater the resistance per turn

the steeper the slope of the corresponding segment of the curve. Similar results may be obtained by tapping the winding at appropriate points and connecting resistors either to ground or in shunt across portions of the winding. Another method involves the use of different spacings for different sections of the winding. Most of these methods are somewhat troublesome in production, but stepped cards have been used in certain cases, such as the RL-B potentiometer, and the tapped winding with shunts is a useful laboratory technique for modifying an existing linear potentiometer to approximate an arbitrary function.

If the approximation to the given function must be so good as to require an unreasonably large number of straight-line segments, some other method must be used. The most direct method is to use a card of continuously variable width, which is in effect an electrical cam. This method has been used successfully in many cases, its principal disadvantages being that it requires the accurate machining of an irregularly shaped edge on the card, and that it places certain limitations on the ratio of maximum to minimum slope and on the maximum rate of curvature of the function. A high ratio of slopes implies a high ratio of maximum to minimum width of the card, and if this ratio exceeds 5 to 1 or perhaps 10 to 1 the card becomes rather fragile at the small end and is difficult to mount. A high rate of curvature of the function implies a rapid change of width of the card, and it is impossible to make the wire stay in place on a rapidly tapering card. A successful example of a shaped-card potentiometer is the RL-256 two-cycle logarithmic unit made by the General Radio Company. The RL-281, made by the Radiation Laboratory, was less successful because of a total angle of 34°, a winding angle of 10° on the contact edge and up to 24° on the curved edge. The maximum safe angle is about 10° to 15°.

The equivalent of a shaped mandrel is a mandrel of constant width with continuously varying wire spacing. This method is not often used since it requires a special cam for the winding-machine feed and since the maximum permissible variation in slope is even less than in the case of the shaped mandrel. Variation of spacing is principally useful as a method of correcting a winding during manufacture. The winding can be continuously compared with a master potentiometer and the error in resistance can be used to control a servomechanism that corrects the feed mechanism through a differential gear. This method is easily applicable to round mandrels wound with bare wire. It is somewhat more difficult with card mandrels and is really complicated with insulated wire; the wire must be bared at the correct point on each turn and the resistance measured as the bared spot is fed onto the mandrel. Such winding machines have been successfully built, however.

Another possibility is to use a tapered wire, which might be obtained

by controlled chemical or electrolytic etching. A variant of this method might be useful in some cases; the winding, which must be made of bare wire, could be partially immersed in a plating solution and varying fractions of each turn could be plated with copper or silver. Such a method was actually used some years ago to produce nonlinear volume-control potentiometers. The plating of high-conductivity material effectively short-circuited a varying length of each turn and had the same effect as the use of a tapered mandrel.

A nonlinear function can be generated by the expedient of slipping wedges or shims between the card and the circular form around which it is stretched. This in effect expands or shrinks certain portions of the card and amounts to the same thing as varying the spacing. This

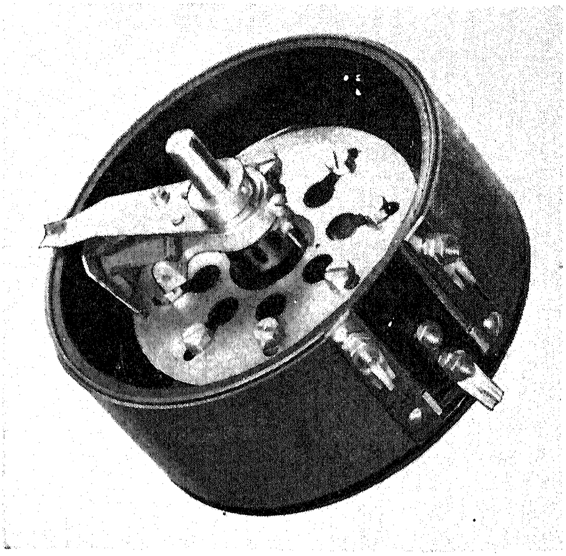


FIG. 8·15.—General Radio Company type 433-AC potentiometer.

method is chiefly useful for adding small corrections. It was used by the Bell Telephone Laboratories in some of the large precision potentiometers for the M-9 and similar computers. In these potentiometers several concentric cards were mounted on the same unit and therefore a correcting cam acting on the contact arm could not be used. The principal difficulty with this method is that of ensuring that the contact is of sufficient length and has uniform pressure at all radii.

The mechanical equivalent of this method is the use of a correcting cam to advance or retard the contact arm with respect to the shaft. This method is also chiefly useful for corrections, and has been very successful in various models of the General Radio Type 433AC potentiometer. This unit is shown in Fig. 8·15. The arm is held to the shaft by

two set screws and rotates with it. The contact spring and its hub can rotate with respect to the shaft, and the spring is pulled toward the observer (in the view shown) by a small helical spring. Its position with respect to the arm is determined by the position of a small bent lever, one end of which bears on a sheet-metal plate. This plate can be warped to form a face cam, whose shape is determined by eight screws. The characteristic can be set exactly to the specified curve at eight points, and the correction varies smoothly and more or less linearly between these points.

One method of generating arbitrary functions begs the question entirely as far as the potentiometer is concerned and places the responsibility on its mechanical drive. Linear potentiometers, in which the contact either rotates on a shaft or slides along a track, can be driven by a cam or linkage mechanism which generates the correct function. This is a common expedient in computers and is particularly well adapted to the linkage mechanisms described in Vol. 27 of this series.

A simple electrical method of generating certain types of curves consists of loading the potentiometer by means of a resistor. Since the output impedance of the potentiometer is a function of the position of the arm (being highest at the position at which the resistance around the circuit to ground is equal in each direction from the contact), the effect of a loading resistor connected to ground will be to "drag down" the output voltage and to give a positive curvature to a previously linear characteristic. If the resistor is connected to the upper end of the potentiometer the curvature will be negative. The method is limited in its application but its simplicity recommends it when it can be used.[1]

One other method of generating certain functions is of great importance. It consists of causing the contact to move in an arbitrary fashion over the surface of a uniformly wound resistance card. This method is most useful for the generation of sine and cosine functions, for which the necessary motion is circular. In some forms of such units the card is stationary and the brush or set of brushes rotates; in others the card is mounted on the shaft and rotates against a stationary set of brushes. One typical example of the rotating-card type is the RL-11 shown in Fig. 8·16. Sine-cosine potentiometers have many uses and have been produced in a number of forms, several of which are shown in the illustrations of this chapter. Other trigonometric functions may be generated by the same method, an example being a tangent function that was used in the gun-order converter of a Navy computer that was designed at the Radiation Laboratory. An arm with a long radial contact moved

[1] R. Hofstadter, "Simple Potentiometer Circuit for Production of the Tangent Function," *Rev. Sci. Instruments*, **17**, 298–300 (August 1946); L. A. Nettleton and F. E. Dole, "Reducing Potentiometer Loading Errors," *ibid.*, **18**, 332–341 (May 1947).

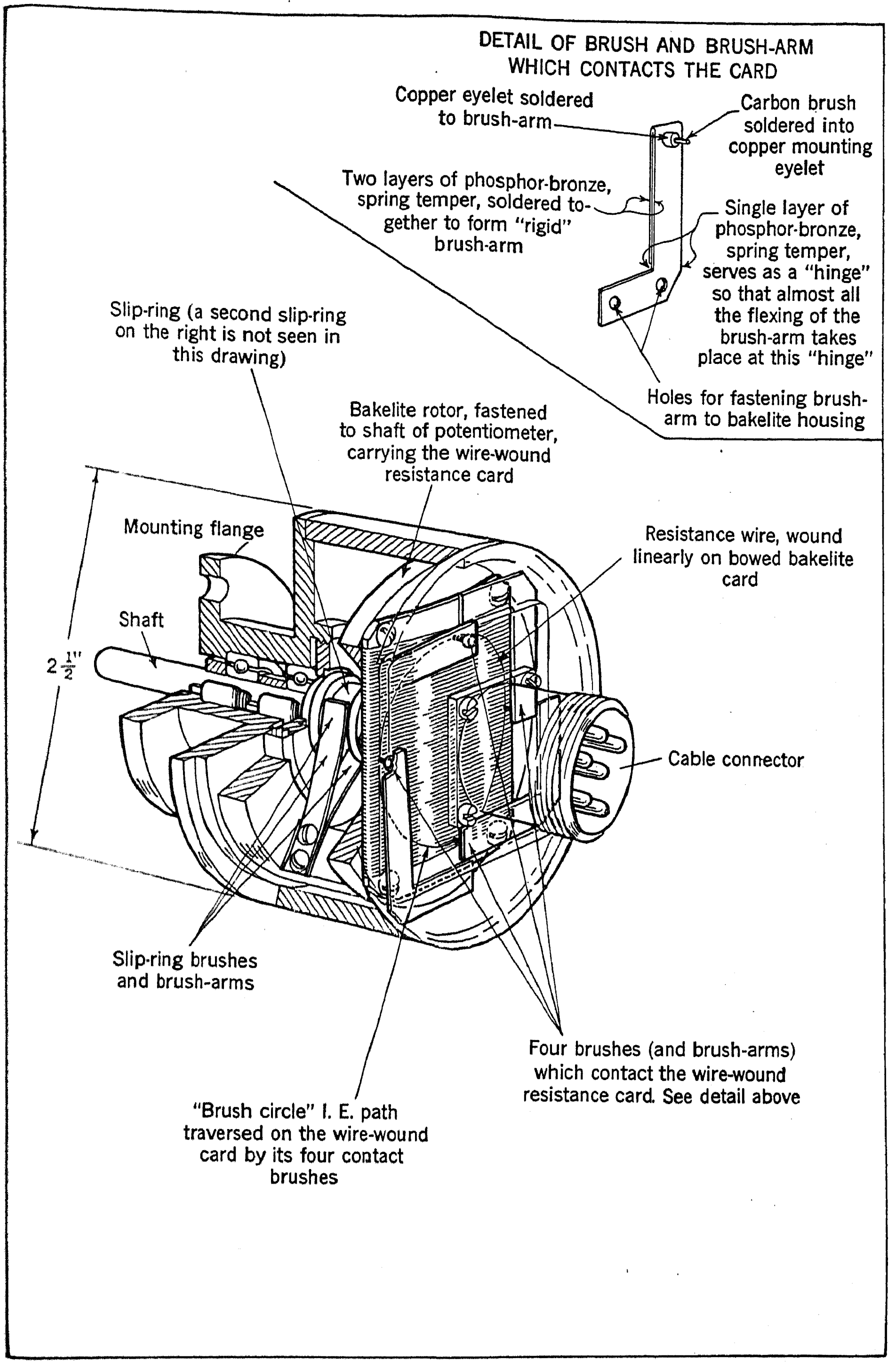


FIG. 8·16.—Construction of potentiometer, type RL-11.

through an angle equal to the computed lead angle and made contact with the edge of a flat card. The resulting electrical output was proportional to the tangent of the lead angle. The method is limited to angles whose tangents are not too large, since there are practical limits to the length of the radial contact, but in this particular case the maximum lead angle was less than 30° and the required length of contact was not excessive.

The methods outlined above are the principal ones that have been used to make nonlinear potentiometers. Others are undoubtedly possible, and a particular potentiometer may use several of the methods in conjunction.

POTENTIOMETER CHARACTERISTICS

8·6. Linearity and Noise.—Probably the most important characteristic of a commercial precision potentiometer is its linearity. This term might be extended to include not only the straightness of the resistance-vs.-shaft-angle curve of a linear potentiometer, but the accuracy of following the prescribed curve for a nonlinear unit. In the discussion which follows, a linear potentiometer will be assumed, but the statements made can be applied to the nonlinear case with obvious modifications. A discussion of test methods will be found in Sec. 8·8.

A discussion of linearity should start out with certain definitions:

1. *Linearity* is the deviation of the curve of the resistance of a potentiometer vs. the shaft angle from a straight line.
2. *Independent linearity* is the deviation when the slope and position of the straight line may be chosen to make the deviation a minimum.
3. *Terminal linearity* is the deviation when the position and slope of the line are defined by the "terminals" of the potentiometer.
4. *Terminals* are the points of 0 and 100 per cent resistance. They may not be accessible to the moving contact.
5. *Total resistance* is the resistance measured between terminals.
6. *Total electrical angle* is the total shaft angle between terminals, assuming that the terminals are accessible to the moving contact.
7. *Brush angle* is the angle between the terminal and the moving contact measured in a clockwise direction as viewed from the shaft end of the unit.
8. *Slope* is the change of resistance caused by movement of the contact through unit angle.
9. *A straight-line resistance function* is any function that satisfies the equation $R = k\theta$, where R is the resistance between the terminal and the contact at a brush angle of θ, and the slope k is a constant.

10. *Deviation* is the plus or minus difference between the actual resistance and the straight-line resistance function at any point, expressed in per cent of the total resistance.
11. *Angular resolution* is the minimum change in brush angle which is necessary to produce a change in resistance. It is a measure of the width of the steps of the fine structure of the resistance curve.
12. *Voltage resolution* is the change in voltage from one step to the next for unit voltage applied between terminals. An equivalent quantity is *resistance resolution,* which is the minimum change in resistance per step as a fraction of the total resistance.

One school of thought has maintained that a mandrel with, say, 1000 turns of wire is capable of giving a resolution of much better than one part in 1000. This idea is based on a theory of "partial contact" which assumes that the contact resistance between the moving contact and the wire varies smoothly and continuously with contact pressure. As the contact starts to leave one wire and climb up one side of the next, the resistance is supposed to increase slowly between the first wire and the contact and to decrease between the second wire and the contact, so that the process of transferring from one wire to the next takes place as though the gap between the wires were bridged by a continuous smooth resistive film. Tests on an oscilloscope linearity tester have refuted this theory, at least as to clean windings and contacts. With metallic surfaces the circuit is either closed or open and no evidence has been found that partial contact can occur. When the contact makes connection simultaneously with two wires it does short-circuit one turn and assumes a potential intermediate between those of the two wires when the short circuit is removed. This in effect doubles the number of steps and increases the resolution of the winding, but it is not what is meant by "partial contact." The effect of short-circuited turns is easily calculable from circuit considerations.

The theory of partial contact may have some validity in the presence of carbon or other materials which do change in resistance with varying pressure. Tests on nonmetallic materials at the Radiation Laboratory were confined to various grades of carbon and graphite brushes, and some evidence for partial contact was found. The contact resistance was so erratic, however, and varied so much with current and with speed of brush movement that the results were not conclusive. Carbon brushes are noisy and should only be used when extremely long life is required and noise can be filtered. Commutation effects dependent upon such an erratic phenomenon would be just as erratic and unpredictable, and the effect must be considered unreliable as a means of increasing the resolution

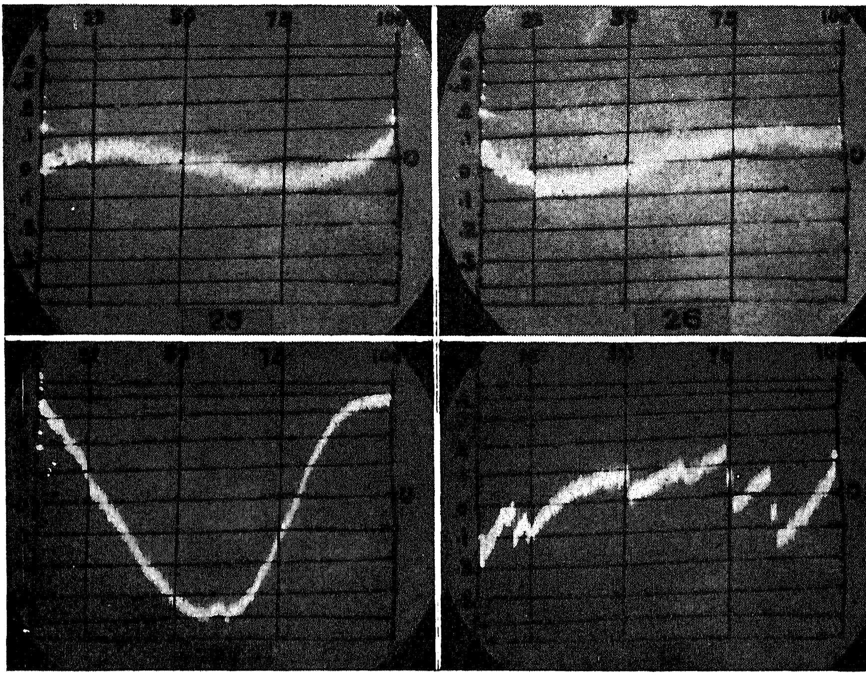
of a potentiometer for low-current conditions. In cases where the current density at the contact surface is very high, however, this conclusion may not hold.

Noise.—The noise generated by a wire-wound potentiometer is of two types, vibrational noise and noise due to imperfect contact. Vibrational noise is due to the jumping of the contact away from the winding, thereby opening the contact circuit. If reasonable care is taken in designing the contact arm, this type of noise should never be produced by external vibration, but in rotating the contact arm, the contact and its supporting spring must constantly climb out of the notch between one pair of wires and slide down into the next. If the arm is rotated too rapidly the contact does not have time to follow the downward slopes and contact is momentarily broken at each wire. The resulting noise appears as "grass" on the oscilloscope linearity tester, and the individual open circuits are often of such short duration that the time constant of the deflection plate and a $\frac{1}{4}$-megohm resistor is too long to permit the spot to reach the edge of the pattern. When the brush speed is sufficiently reduced this type of noise vanishes. The short lightweight contact arm of the RL-270 series potentiometers has never given this sort of trouble at reasonable speeds because of its short vibrational period.

Noise due to imperfect electrical contact is caused by some insulating substance getting between the contact and the surface of the winding. This material may be produced by the wear of the potentiometer itself or it may be a foreign substance. Foreign matter is best excluded by providing a dust-tight enclosure for the potentiometer. The exclusion of dust and the protection of the winding from mechanical damage have resulted in a decided preference for the totally enclosed type of potentiometer. The accumulation on the contact path of products of wear is minimized by the proper choice of contact form, pressure, and material, by proper slip-ring and brush design, by the use of proper bearings, and especially by avoiding the use of lubricant on the windings. No matter what lubricant is chosen, its principal effect is to act as an adhesive that retains noise-producing dirt particles on the contact path instead of permitting them to fall to some portion of the potentiometer where they will do no harm. The use of lubricant may decrease the wear of windings if inferior contacts are used, but the life becomes limited by the development of excessive noise.

8·7. Other Characteristics.—Besides the linearity and noisiness of a potentiometer certain other mechanical and electrical characteristics are of importance. The conditions necessary for the production of a stable and accurate winding were enumerated in Sec. 8·1. Careful assembly and extreme cleanliness were mentioned there but should be emphasized again. Figure 8·17 shows linearity oscillograms of a unit in which various

errors of technique were intentionally made. Figure 8·17*a* shows the oscillogram of the unit as received; the linearity was ±0.10 per cent. One of the card clamping screws was loosened, permitting the card to slip slightly on the form, and the screw was retightened. As shown by Fig. 8·17*b* the form of the deviation curve was changed, although the



(*a*) (*b*) (*c*) (*d*)

FIG. 8·17.—Effects of incorrect assembly techniques.

over-all linearity remained the same. The card was then loosened and displaced radially by $\frac{3}{64}$ in. at the 80 per cent point. This simulated the effect of a nonconcentric form, and resulted in an error of ±0.42 per cent, as in Fig. 8·17*c*. Finally the card was removed and replaced, the technician taking care to have his hands smeared with grease, dirt, and brass filings, as would be the case in the average machine shop or laboratory where no care is taken as to cleanliness. Brass filings were visible on the surface of the winding before reassembly. After reassembly, as shown by Fig. 8·17*d*, the deviation was ±0.19 per cent and seven or eight short circuits were evident on the oscillogram.

Total Resistance.—The total resistance of a potentiometer winding depends upon the surface area of the winding form, the winding pitch, and the resistivity of the wire. If small-diameter wire is used care must be taken to maintain uniform tension on the wire throughout the winding process. In the case of units intended for military use the minimum wire

size is often limited by Service specifications. High-resistance alloys other than those of the Nichrome family usually have comparatively poor wear resistance and short life when used in potentiometers, although it is possible that other suitable materials will become available in the future. At the present time resistances up to 0.5 megohm can be obtained in the large 5-in. potentiometers such as the RL-255 and General Radio 433 types. The maximum resistance values for various types are given in the tables at the end of this chapter.

Minimum total resistance is limited primarily by the requirements of resolving power, which depends upon the winding pitch. Obtaining a low resistance is seldom a serious problem since the potentiometer can always be shunted with a fixed resistor unless it is necessary to work into a low impedance, and in such cases it is often possible to redesign the circuit to permit using a higher value of resistance.

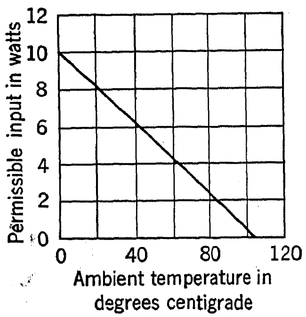


FIG. 8·18.—Power dissipation of type RL-270 potentiometer.

Dissipation Rating.—The maximum power dissipation of a potentiometer winding is usually limited by the maximum permissible operating temperature, which is 105°C for most materials used in potentiometer construction. Power ratings are given for most of the units listed in the tables below. A curve of permissible power input vs. ambient temperature is given for the RL-270 potentiometer in Fig. 8·18. Temperatures were obtained from a thermocouple in a hole drilled in one end of the copper-wire mandrel. The determination of the hot-spot temperature of windings on nonmetallic mandrels is a matter of considerable difficulty, although the average temperature may be determined from resistance measurements if the wire has a sufficiently large temperature coefficient of resistance. Such a determination would ordinarily entail very precise resistance measurements.

The power-handling ability of a potentiometer may also be limited by the permissible change in resistance if the circuit conditions call for an accurate value of total resistance and if the temperature coefficient of the winding is high.

The power-dissipation rating of a potentiometer is not usually a serious limitation to its use. Excessive ambient temperatures may force the unit to be derated, and ambient temperatures over 100°C would be impractical for units of ordinary construction. At the other end of the scale, low temperatures may cause trouble either through excessive change of total resistance or through increased torque requirements due to congealed bearing lubricant.

Torque Requirements.—The torque requirements of commercial potentiometers vary over a considerable range but are of the order of a few inch-ounces for most units. Torques of a few thousandths in.-oz. will operate the tiny units produced by the G. M. Giannini Company and listed in the tables; large units with long contact arms, heavy contact pressures, and poor bearings will require more torque than the average. It may be stated that the torque requirements of the average inexpensive wire-wound potentiometer are excessive, due principally to poor bearings and poorly designed contacts and contact arms. The use of either ball or powdered-metal antifriction bearings and the substitution of better contacts will greatly decrease the torque and improve the characteristics of the average potentiometer.

8·8. Test Methods and Equipment.—The potentiometer development work of the Radiation Laboratory involved such a volume of time-consuming measurements and tests that it was necessary to construct a number of automatic and semiautomatic testing devices. The more important test techniques and pieces of test equipment will be briefly described in this section.

Linearity Tests.—All methods of testing linearity are based eventually on a series of point measurements. These point measurements may be made either as resistance measurements or as voltage-ratio measurements. The latter are preferable since they eliminate the effects of thermal changes in resistance and of contact potentials, and involve less calculation than the resistance-measurement method. Voltage-ratio measurements were made by a null method shown schematically in Fig. 8·19. The standard used was a potential divider of the Kelvin-Varley slide type, with three decades of eleven resistors each and a slidewire. The null indicator was a vacuum-tube voltmeter of special design, based on a circuit by Roberts.[1] An accurate protractor coupled to the shaft of the unit under test is used for angular measurements. A push-button decade attenuator was used for convenience in approaching the null point. A sufficient d-c voltage was applied to the circuit to give an easily detectable voltage for the smallest per cent error to be measured. A photograph of the whole assembly is shown in Fig. 8·20.

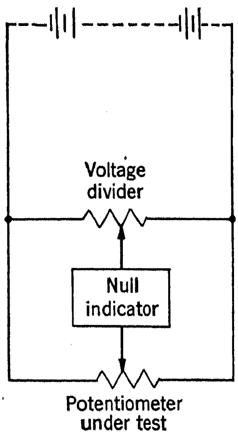


FIG. 8·19.—Basic circuit for ratio measurements.

Voltage-ratio measurements of low-resistance units were made at 60 cps, using an oscilloscope as a null indicator. The use of low frequency

[1] Shepard Roberts, "A Feedback Micro-microammeter," *Rev. Sci. Instruments*, **10**, 181–183, June 1939.

minimized errors due to stray capacitance and permitted measurements of almost four-place accuracy. It had the disadvantage that the null was somewhat obscured by the slight residual phase shift. A low-resistance voltage divider would probably result in considerable improvement.

The linearity figure derived from point measurements is a compromise between independent and terminal linearity. The straight-line function from which the deviations are determined is based upon two measured points near the ends of the winding. The actual end points are avoided because the contact may have touched the riser, or the contact arm may have been sprung slightly upon touching the stop. The sum of the

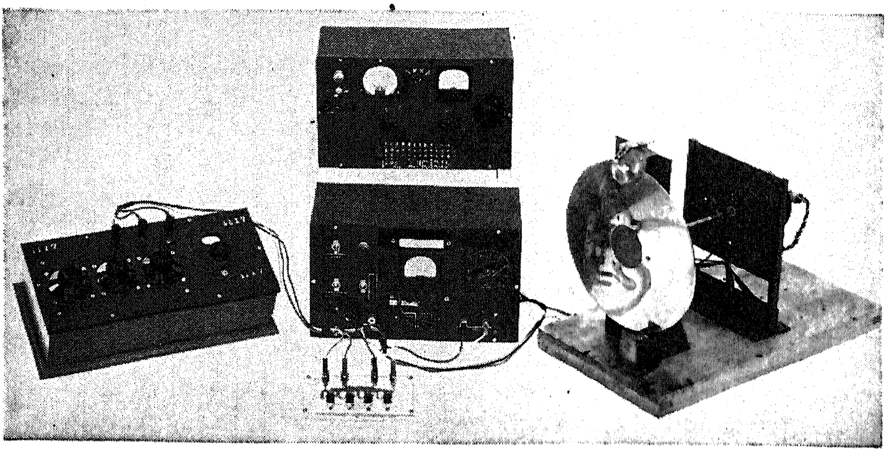


FIG. 8·20.—Point-measurement linearity test assembly.

maximum plus and the maximum minus deviations divided by two gives the linearity figure for the potentiometer. The acceptance of the two measured points near the ends of the winding as defining the straight-line function avoids the more complicated calculations necessary to convert the figures to a true independent linearity calculation in which the maximum plus and maximum minus deviations are equal in magnitude and there are at least two separated points at which the deviation is either the maximum plus or the maximum minus.

Continuous-comparison Linearity Measurements.—The time-consuming nature of point measurements and the fact that they yield no information as to deviations between the measured points made necessary the development of a continuous-comparison method. In its earliest form this method employed a master potentiometer of the continuously wound mandrel type coupled directly to the unit under test. A known voltage was applied to the unit under test and to the portion of the master potentiometer that was used. The two potentiometers were rotated together and the vacuum-tube-voltmeter needle was observed to deter-

mine the errors. The time constant of the meter was too great to permit a good picture of the nature of the error curve. This method was quicker than the point method, however, and did give a continuous and more or less repeatable check. A redesign of the method employing a new and much more accurate master potentiometer and cathode-ray-tube presentation of the error signal resulted in a practically perfect method for the purpose. The error-voltage vs. brush-angle trace presented on the long-persistance P7 screen of the oscilloscope makes accurate readings of the linearity easy. The entire picture of the behavior of the potentiometer is presented to the operator, and nothing is left to chance or memory. The CRT picture also gives much information about the potentiometer beside its linearity. A permanent record may be made by photographing the CRT trace with a standard 35-mm oscilloscope camera. A photograph of the entire assembly of equipment for continuous linearity testing is shown in Fig. 8·21.

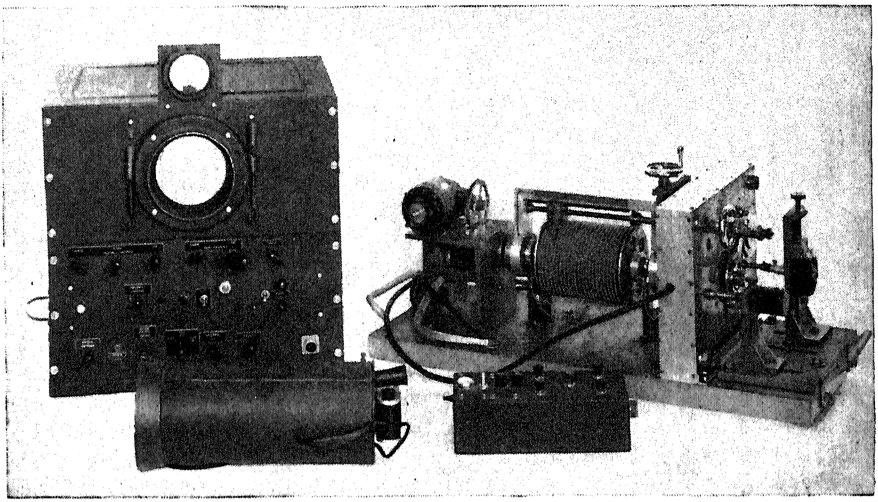


FIG. 8·21.—Continuous linearity testing assembly.

A comparison of the results obtained by the point method and the continuous-comparison method is of interest. Table 8·2 gives the results of measurements on a particular potentiometer and the computed "terminal" linearity, independent linearity, and compromise linearity. Figure 8·22 shows the curve obtained on the same unit with the comparison linearity tester.

The figures for terminal linearity in Table 8·2 illustrate the difficulty of determining the position of the "real" terminal. The same decade ratio was obtained for all brush angles between 239°9′ and 238°45′. This was the lowest ratio obtainable but was not zero because of the

TABLE 8·2.—TYPICAL POINT-MEASUREMENT LINEARITY TEST

Laboratory data		"Terminal" linearity		Independent linearity		Compromise linearity	
Protractor angle	Decade ratio	Calculated ratio	Per cent deviation	Calculated ratio	Per cent deviation	Calculated ratio	Per cent deviation
239°9′	0.0010	......	....	......	....	......	....
238°45′	0.0010	......	....	......	....	......	....
238°57′	0.0010	0.0010	....	0.0024	0.14	......	....
230°	0.0312	0.0308	0.04	0.0322	0.10	0.0312	....
220°	0.0644	0.0642	0.02	0.0656	0.12	0.0645	0.01
210°	0.0976	0.0975	0.01	0.0989	0.13	0.0979	0.03
200°	0.1310	0.1309	0.01	0.1323	0.13	0.1312	0.02
190°	0.1644	0.1642	0.02	0.1656	0.12	0.1646	0.02
180°	0.1984	0.1976	0.08	0.1990	0.06	0.1979	0.05
170°	0.2312	0.2309	0.03	0.2323	0.11	0.2312	0.00
160°	0.2652	0.2642	0.10	0.2656	0.04	0.2646	0.06
150°	0.2986	0.2976	0.10	0.2990	0.04	0.2979	0.07
140°	0.3327	0.3309	0.18	0.3323	0.04	0.3313	0.14
130°	0.3661	0.3643	0.18	0.3657	0.04	0.3646	0.15
120°	0.4004	0.3976	0.28	0.3990	0.14	0.3980	0.24
110°	0.4336	0.4309	0.27	0.4323	0.13	0.4313	0.23
100°	0.4666	0.4643	0.23	0.4657	0.09	0.4646	0.20
90°	0.5003	0.4976	0.27	0.4990	0.13	0.4980	0.23
80°	0.5338	0.5310	0.28	0.5324	0.14	0.5313	0.25
70°	0.5668	0.5643	0.25	0.5657	0.11	0.5647	0.21
60°	0.5999	0.5977	0.22	0.5991	0.08	0.5980	0.19
50°	0.6334	0.6310	0.24	0.6324	0.10	0.6313	0.21
40°	0.6670	0.6643	0.27	0.6657	0.13	0.6647	0.23
30°	0.7004	0.6977	0.27	0.6991	0.13	0.6980	0.24
20°	0.7333	0.7310	0.23	0.7324	0.09	0.7314	0.19
10°	0.7667	0.7644	0.23	0.7658	0.09	0.7647	0.20
0°	0.7991	0.7977	0.14	0.7991	0.00	0.7981	0.10
350°	0.8322	0.8311	0.11	0.9325	0.03	0.8314	0.08
340°	0.8654	0.8644	0.10	0.8658	0.04	0.8647	0.07
330°	0.8985	0.8977	0.08	0.8991	0.06	0.8981	0.04
320°	0.9310	0.9311	0.01	0.9325	0.15	0.9314	0.04
310°	0.9649	0.9644	0.05	0.9658	0.09	0.9648	0.01
300°	0.9981	0.9978	0.03	0.9992	0.11	0.9981	0.00
299°27′	0.9996	0.9996	0.00	1.0010	0.14	......	....
299°39′	0.9996	......	....	......	....	......	....
299°12′	0.9996	......	....	......	....	......	....

resistance from the first wire of the winding out to the terminal connection. The construction of the contact and winding were such that a setting half way between these two angles would not place the contact directly above the first wire, as shown in Fig. 8·23. In the calculations of Table 8·2 the half-way point was assumed to correspond to the mini-

mum voltage ratio 0.0010 in spite of the resulting error, and a similar procedure was used at the other end of the winding. These points corresponded to apparent errors of about −0.15 per cent at each end of

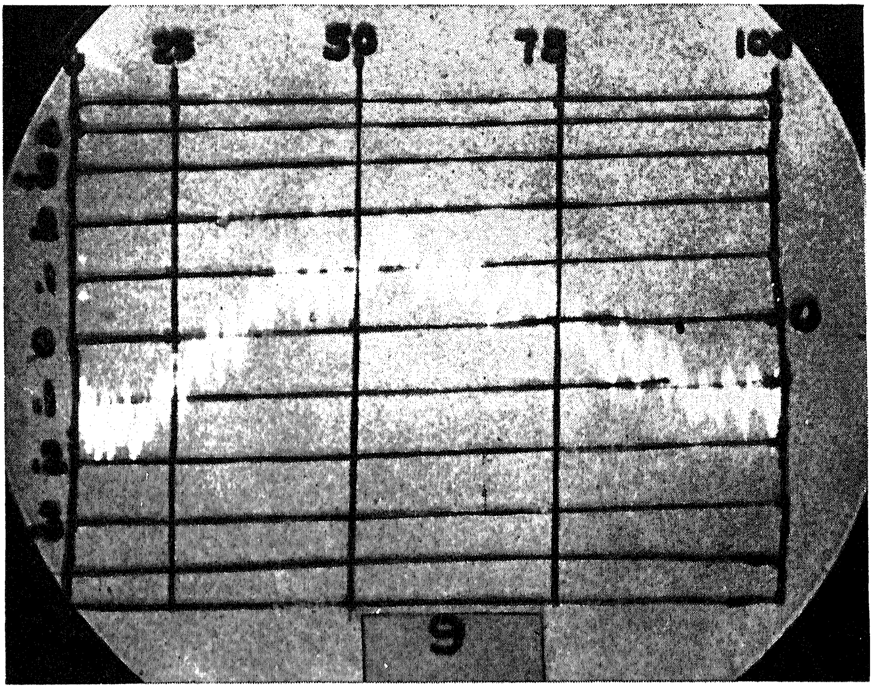


FIG. 8·22.—Linearity test oscillogram of unit of Table 8·2.

the oscillogram of Fig. 8·22. The accuracy of the decade voltage divider used for the point method was about ±0.001 per cent. The master potentiometer used in the comparison tests was accurate to about ±0.03 per cent when checked at 48 points against the voltage divider. The oscillogram discloses a cyclic error of about 0.06 per cent spread due to a mechanical error in the winding machine used in making the test potentiometer.

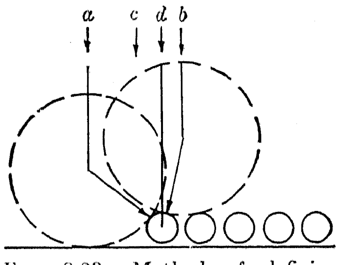


FIG. 8·23.—Method of defining terminal position.

Further Developments.—Linearity and accuracy testers employing CRT presentation of error data give very satisfactory results. To gain the full benefit of the method the master potentiometer must have sufficient accuracy and resolution, and it requires much time and effort to construct a suitable master. Improvements are also desirable in the electronic portions of the equipment. One uncompleted effort in this

direction was a linearity tester for potentiometers with resistances to 10 ohms, which was under development at the time of the termination of the Radiation Laboratory. This tester was to apply 400 to 500 cps a-c to the unit under test and to operate the vertical error amplifier entirely on alternating current with a negative pip applied to the CRT cathode to brighten the tube momentarily at the appropriate time in each cycle. Sufficient experimental work was done before termination to demonstrate that the plan was feasible and that a few more weeks' work would permit turning a design over to the shop for construction.

8·9. Commercial Potentiometers.—This section will describe a number of the commercial precision potentiometers that are available on the market. At the time of writing it is not known whether all of the types enumerated here will continue to be manufactured, and it is known that at least one of the companies that has been producing potentiometers during the war does not intend to continue this production. It is to be expected, however, that any such losses will be made up by other companies, and that the list of available types will increase rather than diminish. The lists of types in this section are by no means complete, but include most of the types with which the Radiation Laboratory was concerned. Various companies other than those listed here manufactured potentiometers for use in equipment of their own manufacture, and may make certain of their units generally available in the future. It is believed, however, that the lists given here do include a fair sample of currently available types.

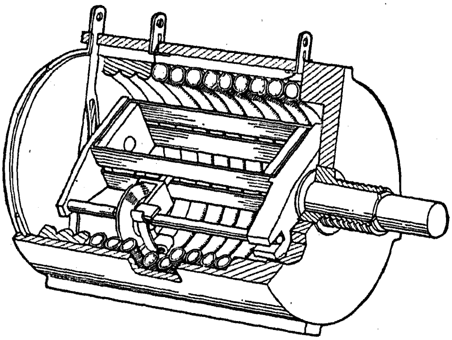


FIG. 8·24.—Helipot construction.

Standard Linear Potentiometers.—The potentiometers listed in Table 8·3 are all of the type in which a single brush makes contact with a terminated winding that has a constant resistance per unit angle. Most of the potentiometers of table 8·3 employ card-type resistance elements and have operating angles of 270 to 300°. The Micropots and Helipots are multiturn units employing Kohlrausch resistance elements: Fig. 8·24

shows the construction of a standard Helipot. The RL-270 series also use Kohlrausch windings but have only a single turn. The shaft rotation is limited by stops in nearly all potentiometers, but a few, such as the RL-270's, use an insulating bridge that permits continuous rotation; the

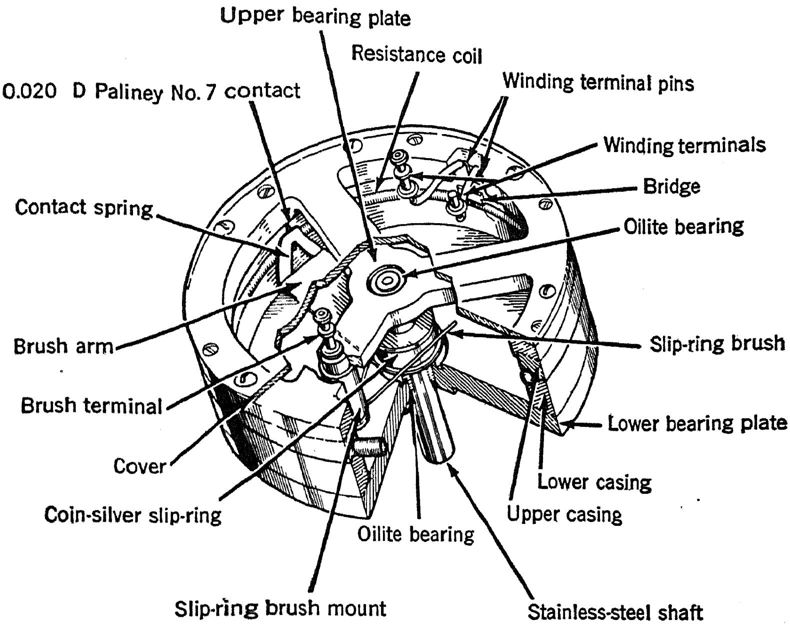


FIG. 8·25.—RL-270 potentiometer construction.

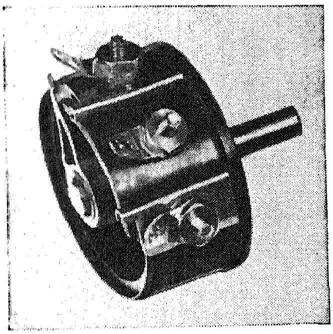


FIG. 8·26.—DeJur No. 12 potentiometer with Paliney contact.

contact rides off the end of the winding onto the bridge and then off the bridge onto the other end of the winding. This bridge is shown in the drawing of the RL-270 in Fig. 8·25.

Most standard linear potentiometers, such as the various models made by DeJur, General Radio, and most of the Muter models, use wound-card

TABLE 8·3.—STANDARD LINEAR POTENTIOMETERS

Maker	Model no.	Resistance, ohms		Dimensions, in.		Weight, oz.	Shaft		Useful angles	Dissipation, watts	Notes*
		Min.	Max.	Diam.	Depth		Diam., in.	Material			
The Muter Co.	301A, 401A	5	20,000	$2\frac{3}{16}$	$1\frac{1}{8}$	3	$\frac{1}{4}$	steel	254°	4	(1), (2)
General Radio Co. and the Muter Co.	214A	10	20,000	$3\frac{3}{16}$	$1\frac{1}{4}$	6	$\frac{1}{4}$	steel	303°	10	(2)
	314A	1,000	100,000	$3\frac{3}{16}$	$1\frac{3}{8}$	6	$\frac{3}{8}$	bakelite	294°	8	(3)
	371A	1,000	100,000	$3\frac{3}{16}$	$2\frac{1}{2}$	8	$\frac{1}{4}$	steel	303°	15	(2), (4)
	471A	10,000	200,000	$3\frac{3}{16}$	$2\frac{5}{8}$	8	$\frac{3}{8}$	bakelite	294°	12	(3)
	433A	10,000	500,000	$5\frac{5}{8}$	$2\frac{9}{16}$	16	$\frac{3}{8}$	bakelite	322°	25	(3), (5)
The Muter Co.	214A Special	1,000	50,000	$3\frac{3}{16}$	$1\frac{1}{4}$	6	$\frac{3}{8}$	bakelite	303°	10	(6)
	314A Special	1,000	100,000	$3\frac{3}{16}$	$1\frac{1}{2}$	6	$\frac{3}{8}$	bakelite	294°	8	(6)
	RL-255	10,000	400,000	$5\frac{5}{8}$	$2\frac{9}{16}$	22	$\frac{3}{8}$	bakelite	322°	25	(6), (7), (8)
DeJur-Amsco Corporation	291, 292	1	20,000	$1\frac{13}{16}$	$1\frac{1}{16}$	3.5	$\frac{1}{4}$	steel	258°	6	(2)
	296	5	25,000	$1\frac{13}{16}$	$1\frac{1}{2}$	3.5	$\frac{1}{4}$	steel	....	8	(2)
	281	50	50,000	3	$1\frac{3}{16}$	3.5	$\frac{3}{8}$	bakelite	248°	4	
	260, 261	100	100,000	3	$1\frac{7}{16}$	5	$\frac{3}{8}$	bakelite	300°	6	
	260T	100	20,000	3	$1\frac{7}{16}$	5	$\frac{3}{8}$	bakelite	300°	6	
	275, 276	100	200,000	3	$2\frac{5}{8}$	7	$\frac{3}{8}$	bakelite	300°	11	
The Muter Co., Fairchild Camera and Instrument Corp.	RL-270	30	50,000	3	$1\frac{3}{8}$	7	$\frac{1}{4}$	stainless steel	$355\frac{1}{2}° \pm \frac{1}{4}°$	6	(6), (7), (9)
	RL-271	20	30,000	$2\frac{3}{32}$	$1\frac{3}{8}$	4	$\frac{1}{4}$	stainless steel	$354° \pm \frac{1}{4}°$	4.5	(6), (7), (9)
Fairchild Camera and Instrument Corp.	RL-272	50	100,000	5	$1\frac{15}{32}$	15	$\frac{1}{4}$	stainless steel	$358° \pm \frac{1}{4}°$	11.8	(6), (7), (9)
Helipot Corp.	680, J1X1	100	30,000	$1\frac{3}{4}$	$1\frac{7}{8}$	$4\frac{1}{4}$	$\frac{1}{4}$	stainless steel	3600°	2	(10), (11)
	690	30	9,000	$1\frac{3}{4}$	$1\frac{1}{4}$	$2\frac{1}{2}$	$\frac{1}{4}$	stainless steel	1080°	1	(10), (11)
Thomas B. Gibbs and Co.	Micropot	2,000	30,000	$1\frac{1}{4}$	$2\frac{1}{8}$	5	$\frac{1}{4}$	steel	3600°	2	(11), (12)
G. M. Giannini and Co. Inc.	B, C	100	2.500	$\frac{7}{8}$	1	$\frac{3}{4}$	$\frac{1}{32}$	steel	270°	2.5	(11), (13)

* Unless otherwise noted all units in the table are flush mounting with brass bearings, have torques of 3 to 15 in.-oz. at normal temperatures, and have linearities of $\pm\frac{1}{2}$ to 1 per cent with standard contact arms. Substitution of correctly designed Paliney No. 7 contact arms will reduce the torque and improve the linearity to ± 0.3 per cent or better. Standard tolerance on total resistance is ± 10 per cent.

(1) 301A is flush mounting; 418A has $\frac{3}{8}$-in. threaded shank for single-hole panel mounting.
(2) Shaft is not insulated from contact arm.
(3) Supplied with linen bakelite protecting strip.
(4) 12-watt dissipation with protecting strip. Muter 371A has $\frac{3}{8}$-in. bakelite shaft.
(5) Type 433AC is same as Type 433A but has correcting cam.
(6) Furnished with Paliney No. 7 contact; linearity ± 0.3 per cent maximum.
(7) Furnished with slip ring and Paliney No. 7 brushes.
(8) Same as 433A except has special contact arm, flange mounting on housing, and ball thrust bearings; torque 2 to 4 in-oz., linearity ± 0.1 per cent.
(9) Flush mounting with centering boss, Oilite bearings, torque 1 in.-oz. Linearity ± 0.1 per cent, resistance tolerance ± 5 per cent.
(10) Linearity ± 0.5 per cent; resistance tolerance ± 5 per cent. Also available with special tolerances.
(11) Has threaded shank for single-hole panel mounting.
(12) Resistance tolerance per specification; linearity ± 0.1 per cent.
(13) Linearity ± 0.5 per cent.

resistance elements secured to the outside of a cylindrical molded plastic form. Table 8·3 gives the principal characteristics of a number of these units, and Figs. 8·25 through 8·28 show four typical units.

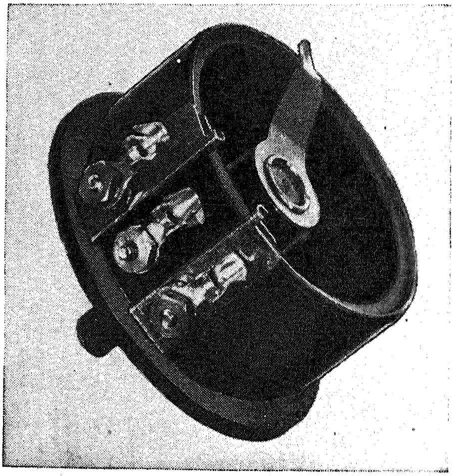


FIG. 8·27.—DeJur Type 261 potentiometer.

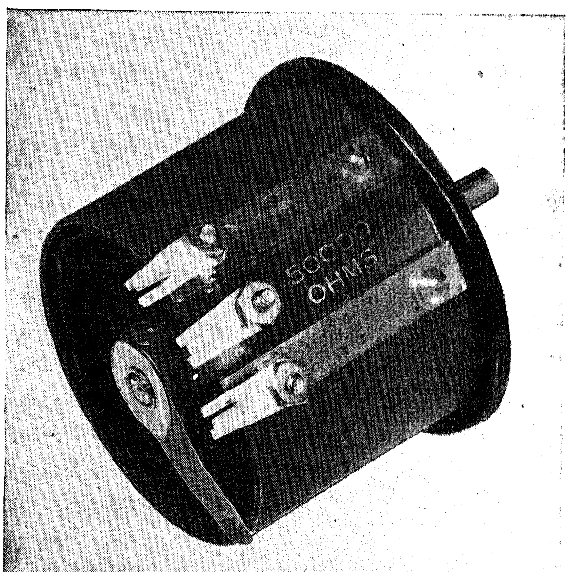


FIG. 8·28.—General Radio Type 371A potentiometer.

Ring Potentiometers.—There are many applications, such as data transmission, for which it is desirable to use a potentiometer that is cap-

able of continuous rotation but that does not have the discontinuous output characteristic of a standard potentiometer with a bridge, such as the RL-270. For these applications a ring potentiometer is commonly used. This is a potentiometer with a continuous winding on a toroidal mandrel,

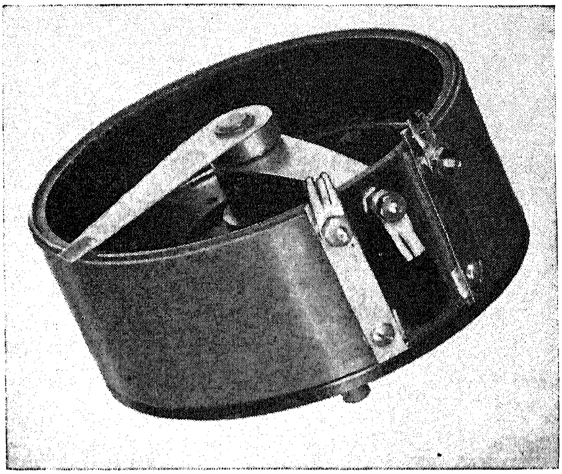


FIG. 8·29.—Muter Type 433A potentiometer.

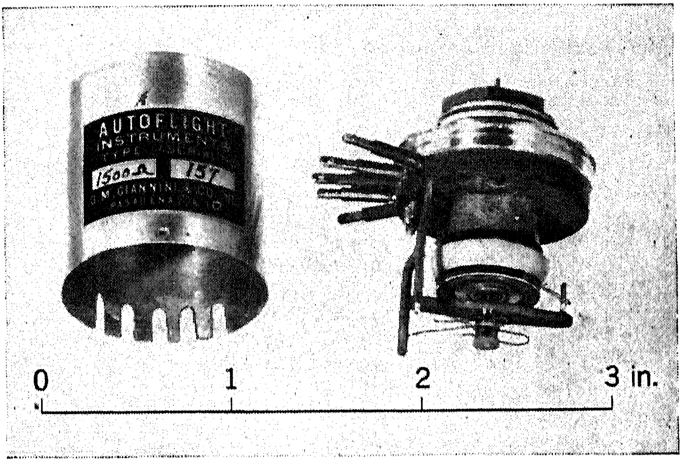


FIG. 8·30.—Giannini Microtorque potentiometer, Type A.

tapped at appropriate points. For angular data transmission to a d-c Selsyn or to a matching potentiometer and servo system it is customary to tap the winding at three points 120° apart and to use two brushes 180° apart, as in the d-c Selsyn system shown in Fig. 10·43. Potentiometers of this type are shown in Figs. 8·30 and 8·31.

For other applications it may be desirable to use other arrangements of taps and brushes. Certain types of radar indicators, for example, use two taps 180° apart and two brushes also 180° apart. If the potentiometer output works into a high impedance such as the plates of an electrostatic

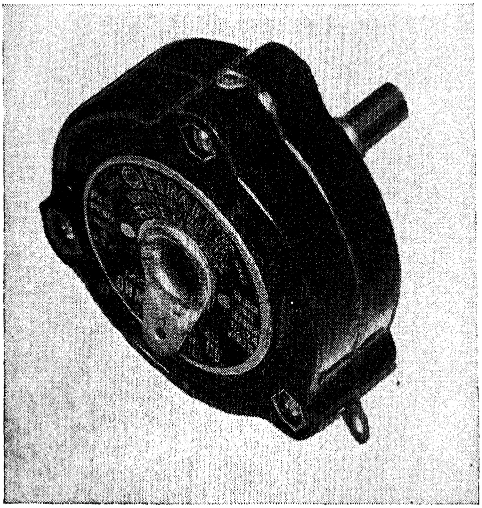


FIG. 8·31.—Ohmite ring potentiometer, model DR-125.

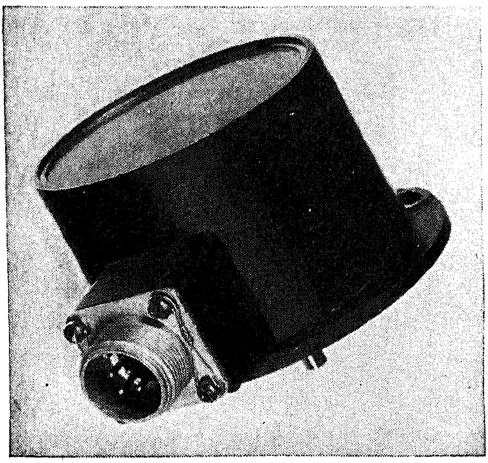


FIG. 8·32.—RL-B potentiometer.

CRT the winding should be linear in order to obtain a linear relationship between output voltage and shaft angle. If the potentiometer feeds current to the deflection coil of an electromagnetic CRT a different characteristic is required. The RL-B potentiometer was given a "hump-backed" characteristic by using a stepped mandrel in order to compensate

TABLE 8·4.—RL-B AND SIMILAR POTENTIOMETERS

Maker	Type	Resistance, ohms	Tolerance, ± per cent	Linearity, ± per cent	Rotation, degrees	Number of brushes	Number of taps	Electrical angle, degrees	Remarks
CTS	RL-B	100	10	2 (or 1.8°)	cont.	2 at 180°	2 at 180°	360	nonlinear ring: gives linear output with CRT deflection coil load
CTS, G	RL-200	6,000	10	....	cont.	1	none	359.4	linear. 0.6° gap
CTS, G	RL-200B	1,500	10	0.5 (Terminal)	cont.	1	none	357	linear. 3° gap
CTS, G	RL-210	1,800	15	0.7	cont.	2 at 180°	2 at 180°	360°	ring
G	RL-225	10,000	5	0.5	cont.	1	none	185°	linear
CTS	RL-225A	10,000	5	0.5	cont.	1	none	185°	linear
CTS	RL-225B	10,000	5	0.75	cont.	1	none	350°	linear
CTS, G	RL-226	5,000	......	1.0	cont.	2 at 180°	2 at 180°	360°	ring
G	RL-226B	20,000	......	1.0	cont.	2 at 180°	2 at 180°	360°	ring
CTS	RL 237A, RL 237B, RL 237C	20,000	+5, −8	1.0 each section	170°	2 at 180°	none	170°	2 independent linear sections on same mandrel
G	RL 273	2,000 to 50,000	5	....	cont.	1	....	350°	linear

As of 1947, it is understood that the Chicago Telephone Supply Co. is no longer making potentiometers of the above types, but that the Gamewell Co. is making all the former CTS precision types.

NOTES: CTS means Chicago Telephone Supply Co.; G means Gamewell Co. All units similar mechanically: have Oilite bearings and $\frac{1}{4}$-in. stainless steel shafts. Weights run from 14 to 14.5 oz.

G. M. Giannini and Co. also make a ring potentiometer, type A, similar to the types B and C of Table 8·3, but with continuous rotation, 2 brushes at 180°, and 3 taps at 120°.

for the droop caused by the output current. The original RL-B sired a large family of variant forms, some of which are listed in Table 8·4; An RL-B potentiometer is shown in Fig. 8·32.

Sine-cosine Potentiometers.—For many applications, particularly for radar PPI displays and for various types of computers, potentiometers are required which give outputs proportional to the sine or cosine of the

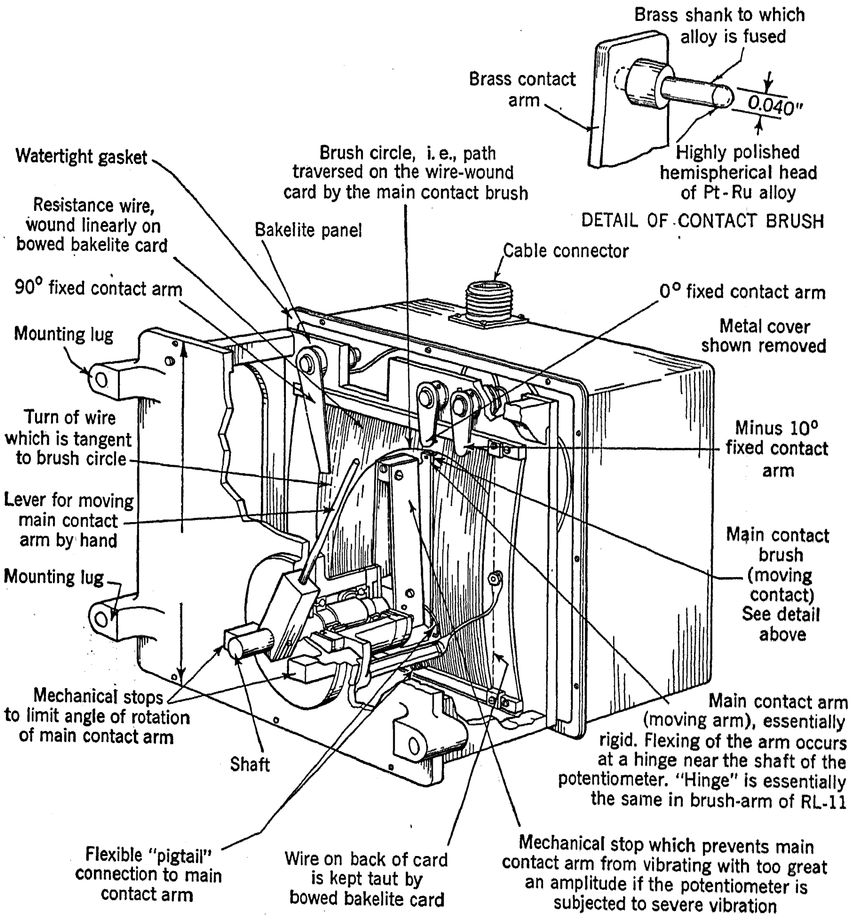


FIG. 8·33.—RL-204 potentiometer construction.

brush angle. The RL-11 potentiometer, which gives both sine and cosine outputs, was shown in Fig. 8·16; a more specialized type, the RL-204, which was never produced in large numbers, is shown in Fig. 8·33. The sine potentiometers which were most extensively used by the Radiation Laboratory were those made by the F. W. Sickles Company, the RL-11C and the RL-14, shown in Figs. 8·34 and 8·35. Both are

flush-mounting flanged rotating-card types with four brushes and ball bearings. The RL-11C is $2\frac{1}{4}$ in. in diameter by $1\frac{13}{16}$ in. deep, with a $\frac{3}{16}$-in. shaft, and weighs $4\frac{3}{4}$ oz. Its torque is $\frac{1}{2}$ in-oz, its total resistance

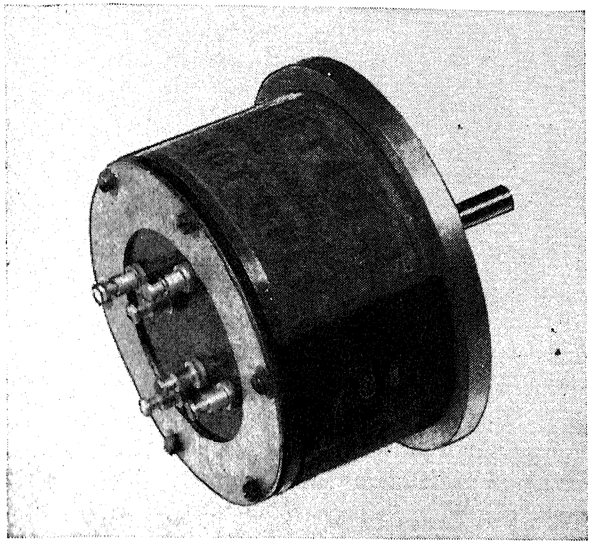


FIG. 8·34.—RL-11C potentiometer.

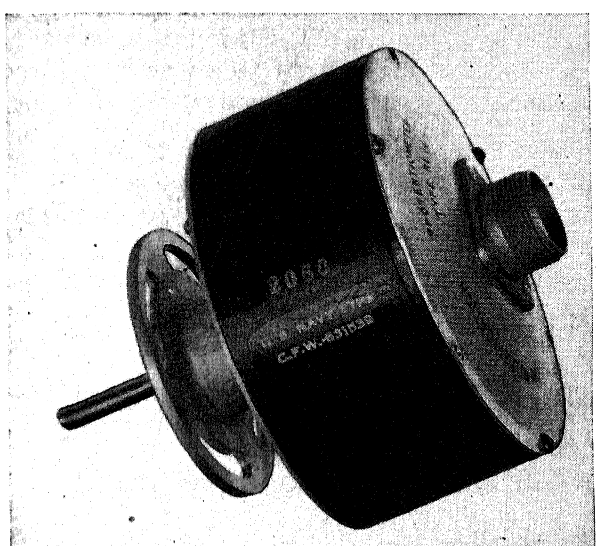


FIG. 8·35.—RL-14 potentiometer.

16,000 ohms $\pm$ 10 per cent, its angular accuracy $\pm 0.35°$, and the radial accuracy of the brush positions ± 0.4 per cent. The RL-14 is a larger unit with carbon brushes for long life (although at a sacrifice of accuracy

and noise characteristics), a diameter of $4\frac{3}{8}$ in., a depth of $4\frac{5}{16}$ in., a weight of 29 oz, and a $\frac{1}{4}$-in. shaft. Its total resistance is 34,000 ohms ± 10 per cent, angular accuracy 0.5°, and radial accuracy 0.65 per cent. The RL-14MS is similar except that it uses Paliney brushes and has a 35,000-ohm total resistance. Its angular accuracy is 0.35° and its radial accuracy is 0.4 per cent. The dissipation rating of the RL-11C is $1\frac{1}{2}$ watts and of the RL-14, $3\frac{1}{2}$ watts.

Nonlinear Potentiometers.—Nonlinear potentiometers are ordinarily designed for each particular application, and therefore are not listed by model number in ordinary catalogues. Several manufacturers will make up such units to order, and should be consulted as to the practicability of fitting the particular curve desired. The General Radio Company has made various types, using the 371 and 433 frames, and the Fairchild Camera and Instrument Corporation has recently announced a line of nonlinear potentiometers with a diameter of $1\frac{5}{8}$ in. and a maximum resistance (for a linear unit) of 100,000 ohms. The Fairchild units can be ganged on a common shaft. The electrical rotation can be as large as 310°, and the mechanical rotation can be either continuous or limited by stops. Fairchild guarantees to fit a given curve (within necessary limitations of slope and curvature) within 1 per cent.

Manufacturers of Potentiometers and Components.—The following list of manufacturers of potentiometers and potentiometer components includes only those firms with which the Radiation Laboratory potentiometer group had extensive experience. Other sources of supply of the items mentioned will undoubtedly be found equally suitable.

PRECISION COMMERCIAL POTENTIOMETER MANUFACTURERS

Chicago Telephone Supply Co.*
1142 W. Beardsley Ave.
Elkhart, Ind.

Cinema Engineering Co.
1508 West Verdugo Avenue
Burbank, Calif.

DeJur-Amsco Corporation
Northern Blvd. at 45th St.
Long Island City 1, N. Y.

Fairchild Camera and Instrument Corporation
475 Tenth Avenue
New York 18, N. Y.

Gamewell Co., The
Chestnut Street
Newton Upper Falls, Mass.

General Electric Company
West Lynn, Mass.

General Electric Company
Schenectady 5, N. Y.

General Radio Company
275 Massachusetts Avenue
Cambridge 39, Mass.

G. M. Giannini & Co., Inc.
285 W. Colorado St.
Pasadena 1, Calif.

Thomas B. Gibbs Co.
Div. of George W. Borg Corp.
814 Michigan St.
Delavan, Wis.

* Note: As of 1947, it is understood that both CTS and Sickles have discontinued the manufacture of potentiometers.

Helipot Corporation
1011 Mission St.
So. Pasadena, Calif.

Minneapolis-Honeywell Regulator Co.
2753 Fourth Ave. S.,
Minneapolis, Minn.

Leeds and Northrup Co.
4970 Stenton Ave.
Philadelphia 44, Pa.

The Muter Company
1255 South Michigan Avenue
Chicago, Ill.

F. W. Sickles Co.*
165 Front St.
Chicopee, Mass.

CONTACT MATERIAL MANUFACTURERS

Baker and Company, Inc.
113 Astor Street
Newark 5, N. J.

The International Nickel Company, Inc.
67 Wall Street
New York, N. Y.

The J. M. Ney Company
71 Elm Street
Hartford, Conn.

Instrument Specialties Company, Inc.
Little Falls, N. J.

P. R. Mallory and Co., Inc.
3029 E. Washington St.
Indianapolis 6, Ind.

The H. A. Wilson Company
105 Chestnut Street
Newark 5, N. J.

RESISTANCE WIRE MANUFACTURERS

Driver-Harris Company
201 Middlesex St.
Harrison, N. J.

Hoskins Manufacturing Company
4445 Lawton Avenue
Detroit, Mich.

Wilbur B. Driver Company
150 Riverside Avenue
Newark 4, N. J.

The C. O. Jelliff Mfg. Corporation
200 Pequot Ave.
Southport, Conn.

North American Philips Company, Inc.
100 East 42nd Street
New York 17, N. Y.

SPECIAL RESISTANCE WIRE COATINGS

General Electric Company
Schenectady, N. Y.

Phelps Dodge Copper Products Corporation
Ft. Wayne, Ind.
or, 40 Wall St., New York, N. Y.

POTENTIOMETER VARNISH MANUFACTURER

Brooklyn Varnish Company
Division Wipe-On Corporation
105 Hudson Street
New York, N. Y.

BUFFING WHEEL AND BUFFING COMPOUND MANUFACTURERS

Bacon Felt Company
Winchester, Mass.

Hanson, Van Winkle, Munning Co.
Matawan, N. J.

* See footnote on opposite page.

CHAPTER 9

SPECIAL VARIABLE CONDENSERS

By E. A. Holmes, III

9·1. Phase-shifting Condensers.—The phase-shifting condensers described in this section were primarily intended for the accurate measurement of time intervals in radar systems. The technique used consists of allowing the transmitted pulse to initiate a train of oscillations of known frequency, or of allowing a continuous train of sinusoidal oscillations to initiate the transmitted pulse at the desired instants. The zero-voltage points of either set of these oscillations then constitute a series of accurate time marks. The time measurements can be made continuous by shifting the phase of the oscillations and causing a marker pip to follow a particular zero-voltage point. If the oscillation is shifted in phase by 360°, the resulting wave is indistinguishable from the unshifted wave, but the marker will have moved in time an amount corresponding to 1 cycle of the oscillation. A further shift causes the marker to move a proportional amount farther. The phase shift necessary to make the marker coincide with an echo of the transmitted pulse is then a measure of the time delay of the echo and thus of the distance to the echo-producing object. Details of the circuits and techniques useful for this form of time measurement will be found in Vol. 20, Chaps. 8 and 9 of the Radiation Laboratory Series.

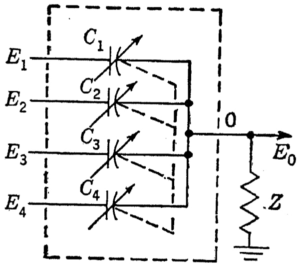


Fig. 9·1.—Schematic diagram of phase-shifting condenser.

The design and construction of the condensers used in shifting the phase of such pulsed or continuous oscillations will form the subject matter of this section. These condensers are by no means useful for this specific purpose alone, but since they were so designed and used, the information given is taken from calculations and experiments for this use. Most of the data, design information, and results are from the work of G. R. Gamertsfelder.[1]

The method of shifting the phase of the oscillations consists of splitting the original oscillation into four separate phases 90° apart by means of

[1] G. R. Gamertsfelder, "Errors in the Continuous-type Condenser Phase Shifter," RL Report No. 633, Dec. 6, 1944.

resistance-capacitance bridges or other phase-shifting devices and recombining these phases in the proper proportions in a capacitance mixer to give a resultant of any desired phase. Specifically, consider Fig. 9·1 in which

$$\begin{aligned} E_1 &= E \sin \omega t, \\ E_2 &= -E \cos \omega t, \\ E_3 &= -E \sin \omega t, \\ E_4 &= E \cos \omega t \end{aligned} \tag{1}$$

The voltages E_1, E_2, E_3, and E_4 are of equal magnitude and are 90° apart in phase.

Let

$$\begin{aligned} C_1 &= D + G \cos \phi, \\ C_2 &= D + G \sin \phi, \\ C_3 &= D - G \cos \phi, \\ C_4 &= D - G \sin \phi, \end{aligned} \tag{2}$$

where D and G are constants ($D \geqq G$) and ϕ is the angular position of the shaft. Equating to zero the sum of the currents flowing to point O gives the equation

$$\begin{aligned} (E_1 - E_O)j\omega C_1 + (E_2 - E_O)j\omega C_2 + (E_3 - E_O)j\omega C_3 \\ + (E_4 - E_O)j\omega C_4 - \frac{E_O}{Z} = 0, \end{aligned} \tag{3}$$

which yields Eq. (4) upon substituting the values of the E's and C's from Eqs. (1) and (2):

$$E_0 = \frac{2EG}{4D + \frac{1}{j\omega Z}} (\sin \omega t \cos \phi - \cos \omega t \sin \phi)$$

or

$$E_0 = \frac{2EG}{4D + \frac{1}{j\omega Z}} \sin (\omega t - \phi). \tag{4}$$

Thus the input voltages are attenuated by the factor $\dfrac{2G}{4D + \frac{1}{j\omega Z}}$ and the phase shift is proportional to ϕ.

There are two condensers (the Cardwell KS-8534 and the Western Electric D-150734) available for 4-phase phase-shifting of this type and a third (the P. J. Nilsen Model 301) for a 3-phase input. Figures 9·2 through 9·5 show the external appearance and the construction of these

condensers. The Western Electric and Nilsen units have the advantages of compactness, complete shielding, higher impedance, and absence of rotary contacts and have therefore been more generally used. The construction of the Western Electric condenser is shown schematically in

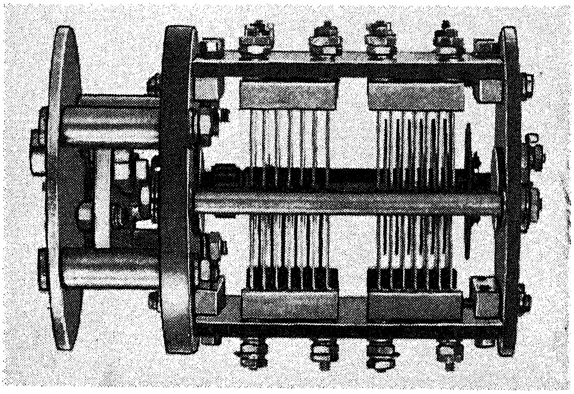


FIG. 9·2.—Cardwell KS-8534 condenser.

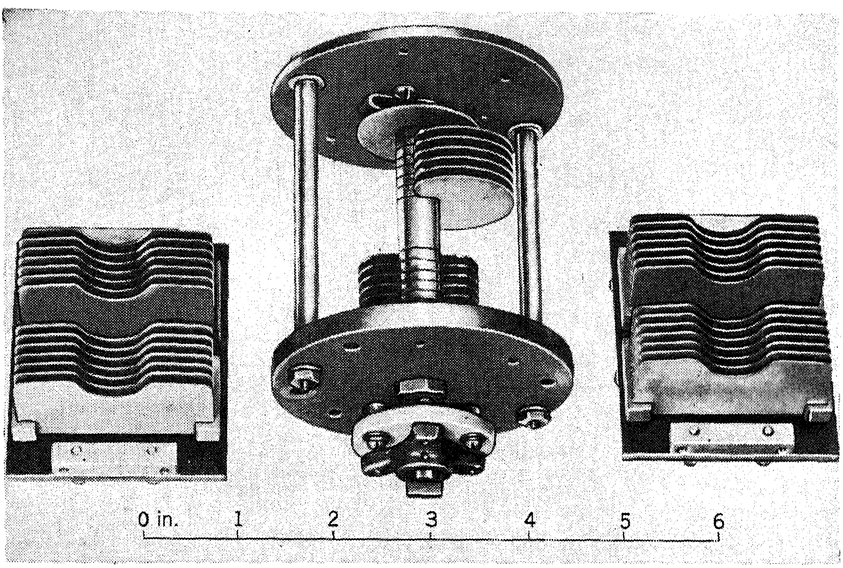
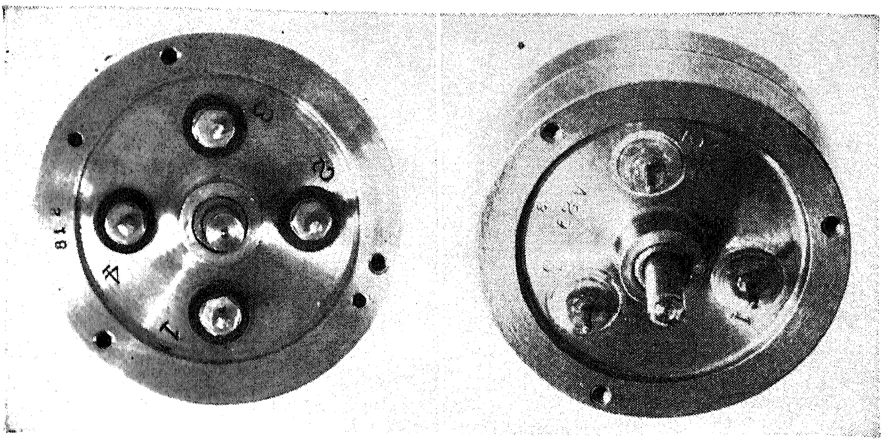


FIG. 9·3.—Cardwell condenser disassembled.

Fig. 9·6; the Nilsen condenser is of the same general construction except that its top plate is divided into three instead of four equal sectors. The variation of capacitance is produced in both units by the rotation of an eccentric Mycalex plate between the sectoral and the circular electrodes, the shapes of the eccentrics being different in the two cases. It happens



(a) (b)

FIG. 9·4a.—Western Electric condenser.
FIG. 9·4b.—Nilsen condenser.

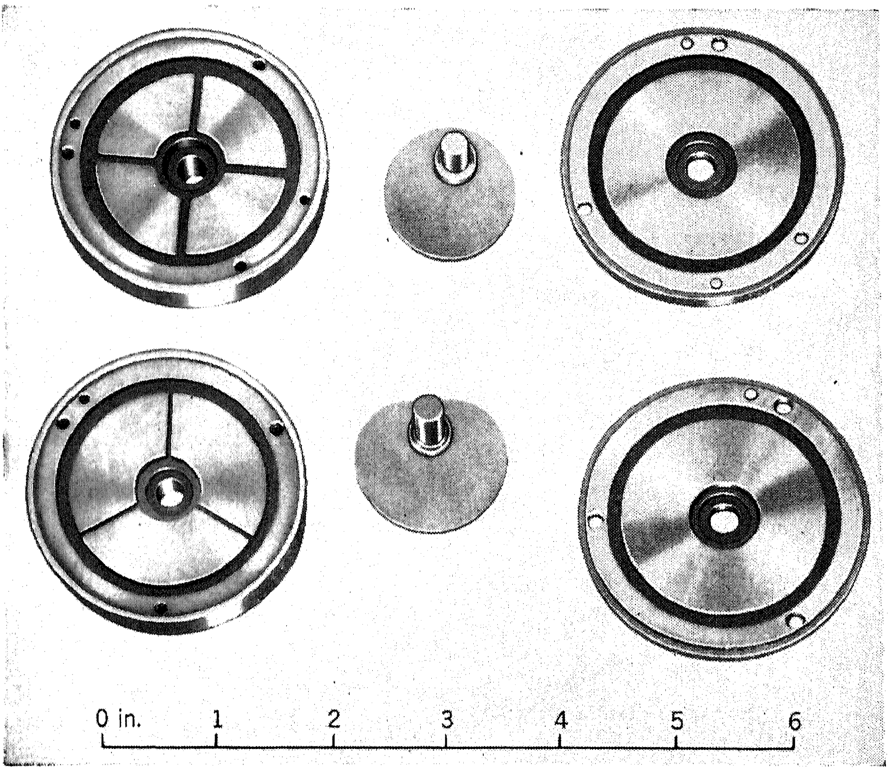


FIG. 9·5.—Western Electric and Nilsen condensers disassembled.

that the theoretically correct shape for a four-electrode condenser is almost a perfect circle, and in the interests of simplifying manufacture, the Western Electric rotor was made circular.

Performance of a Circular Rotor.—The polar equation for a circle of radius a whose center is at a distance b from the origin is

$$\rho = b \cos \theta + \sqrt{a^2 - b^2 \sin^2 \theta}. \qquad (5)$$

From Fig. 9·7 the area common to this circle and to a quadrant

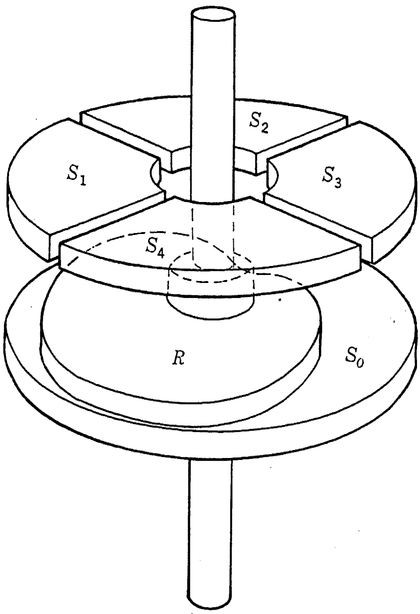


FIG. 9·6.—Mechanical schematic diagram of 4-phase condenser. R, eccentric dielectric rotor; S_1, S_2, S_3, S_4, input sectors; S_o, output stator ring.

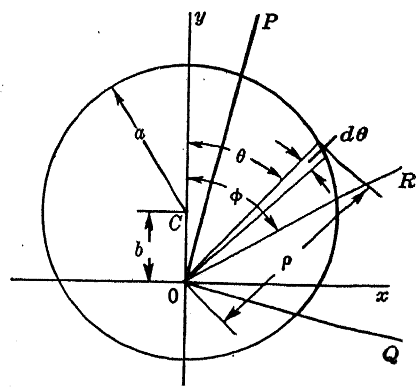


FIG. 9·7.—Geometry of circular rotor.

POQ whose bisector OR makes an angle ϕ with the direction Oy is given by

$$A = \int_{\phi-\frac{\pi}{4}}^{\phi+\frac{\pi}{4}} \frac{\rho^2}{2}\, d\theta. \qquad (6)$$

When the value for ρ is substituted from Eq. (5),

$$A = \frac{1}{2}\int_{\phi-\frac{\pi}{4}}^{\phi+\frac{\pi}{4}} (b^2 \cos^2 \theta + a^2 - b^2 \sin^2 \theta + 2b \cos \theta \sqrt{a^2 - b^2 \sin^2 \theta})\, d\theta. \qquad (7)$$

The first three terms of this equation can be integrated directly. The fourth may be transformed into a series that converges sufficiently rapidly to permit the omission of terms in $\sin \theta$ of powers higher than the third without appreciable error. After thus integrating and rearranging terms, Eq. (7) becomes

$$A = \frac{a^2}{2}\left[\frac{\pi}{2} + \left(4k - \frac{k^3}{2}\right)\frac{\cos\phi}{\sqrt{2}} + k^2\cos 2\phi + \frac{k^3\cos 3\phi}{6\sqrt{2}}\right], \tag{8}$$

where $k = b/a$. This equation is of the form

$$C_1 = D + G\cos\phi + F\cos 2\phi + N\cos 3\phi + \cdots . \tag{8a}$$

For the Western Electric condenser, $k = 0.53$; hence the equation becomes

$$C_1 = \frac{a^2}{2}(1.57 + 1.55\cos\phi + 0.28\cos 2\phi + 0.018\cos 3\phi). \tag{9}$$

The effect that a circular rotor has on the accuracy of phase shift may be found by substituting the values of the E's from Eqs. (1) and of the C's from Eqs. (2) in Eq. (3), which yields after rearrangement,

$$2E[\sin\omega t(G\cos\phi + N\cos 3\phi) - \cos\omega t(G\sin\phi - N\sin 3\phi)] = E_O\left(4D + \frac{1}{j\omega Z}\right). \tag{10}$$

It should be noted that this expression contains no terms in 2ϕ.

Let

$$G\cos\phi + N\cos 3\phi = S\cos\gamma \tag{11a}$$

and

$$G\sin\phi - N\sin 3\phi = S\sin\gamma \tag{11b}$$

where γ represents the angle of phase shift of E_O in the expression

$$E_O = \frac{2ES\sin(\omega t - \gamma)}{4D + \dfrac{1}{j\omega Z}}. \tag{12}$$

From Eq. (11) it can be shown that

$$\sin(\phi - \gamma) = \frac{N}{G}\cos 3\phi\sin\gamma + \frac{N}{G}\sin 3\phi\cos\gamma. \tag{13}$$

Since $\phi - \gamma$ will be small,

$$\phi - \gamma \approx \frac{N}{G}\sin 4\phi. \tag{14}$$

Thus the error $\phi - \gamma$ is of period $\pi/2$ and has an amplitude of N/G radians. From Eq. (9) it can be seen that $N/G = 0.018/1.55 = 0.0116$, and the maximum error is therefore about 0.7°.

A rotor constructed according to the polar equation,

$$\rho = \sqrt{L + M\cos\theta}, \tag{15}$$

the latter the plates are molded into place and finish-machined after molding.

The stator plates of the Nilsen condenser are alike except that the plate that is to form the sectors has three input lead pins brazed to its back whereas the output ring has only one. These rings are provided with undercut grooves on their backs to provide a good grip for the polystyrene, which is held to the case by flowing out into three counter-

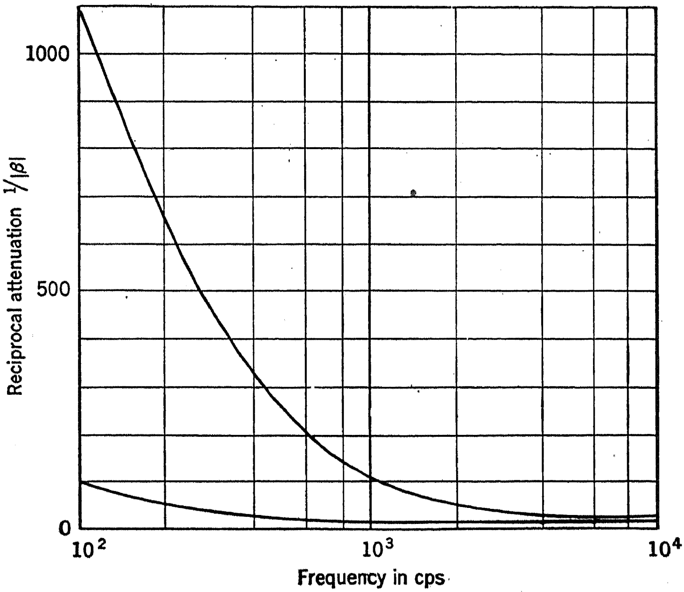


FIG. 9·9.—Attenuation with Western Electric condenser. Upper curve: load resistance 10^6 ohms, shunt capacitance 11 $\mu\mu$f. Lower curve: load resistance 10^7 ohms, shunt capacitance 1 $\mu\mu$f.

sunk holes that also serve to carry the leads. The semifinished case and ring are placed in a die and the molding operation is performed, making case, insulation, and stator electrode a single solid mechanical unit.

After it is molded, the assembly is placed in a lathe, and all interior and mating surfaces are finished in a single setup. This process ensures that the mating surfaces marked *a* in Fig. 9·10 will be truly concentric with the bushing bore and with the inner and outer surfaces of the electrodes, and that the electrode surfaces will be plane, correctly spaced, at right angles to the axis, and parallel with the mating surfaces *b*. The final operation in the case of the half that bears the sectors is to set it up on a rotary table and to mill three radial slots that cut the ring into three 120° sectors. The technique of machining all important dimensions in a single setup produces a unit with excellent over-all dimensional accuracy without having to hold extremely close dimensions on the

The load impedance of the condenser, including the capacitance of its output plate to ground, is Z. It can be written

$$Z = \frac{1}{\frac{1}{R} + j\omega(C + C')}, \tag{25}$$

where C' is the output capacitance of the phase shifter, and R and C are the parallel input resistance and capacitance of the amplifier that follows the phase shifter. Thus

$$\beta_4 = \left| \frac{2G}{4D + C + C' + \frac{1}{j\omega R}} \right| = \frac{2G}{\sqrt{(4D + C + C')^2 + \frac{1}{\omega^2 R^2}}} \tag{26}$$

and

$$\beta_3 = \left| \frac{3G}{6D + 2\left(C + C' + \frac{1}{j\omega R}\right)} \right| = \frac{3G}{\sqrt{(6D + 2C + 2C')^2 + \frac{4}{\omega^2 R^2}}} \tag{27}$$

for the two cases. For the Western Electric condenser $G = 0.75$ $\mu\mu$f, $D = 1.5$ $\mu\mu$f, and $C' = 12.7$ $\mu\mu$f. The corresponding quantities for the Nilsen condenser have not been measured, but it is known that their respective values are only slightly greater than those for the Western Electric condenser.

In Fig. 9·9 the reciprocal of the attenuation factor for the Western Electric condenser has been plotted as a function of frequency for two sets of values of R and C. The attenuation is less when the 3-phase condenser is used. By using a cathode follower after the phase shifter it should be possible to work at frequencies as low as 100 cps.

Accuracy of Phase Shift.—Sufficient data are not available to specify accuracy in terms of phase shift vs. shaft angle for any of the condensers described here. It is known that the Western Electric condenser can be relied upon to shift the phase of the output voltage to within 2°, and the Nilsen condenser to within 1° of the position of the rotor. Although the variation of capacitance of any one element of the Western Electric condenser is only approximately a sine function, when the condenser is used as described above the errors of opposite pairs of elements very nearly cancel, and the net effect is therefore close to that of a true sine condenser.

Mechanical Design of Western Electric and Nilsen Condensers.—The design and construction of the Western Electric condenser are similar to those of the Nilsen unit, the principal difference being that in the former the stator plates are made separately and screwed in place, whereas in

the latter the plates are molded into place and finish-machined after molding.

The stator plates of the Nilsen condenser are alike except that the plate that is to form the sectors has three input lead pins brazed to its back whereas the output ring has only one. These rings are provided with undercut grooves on their backs to provide a good grip for the polystyrene, which is held to the case by flowing out into three counter-

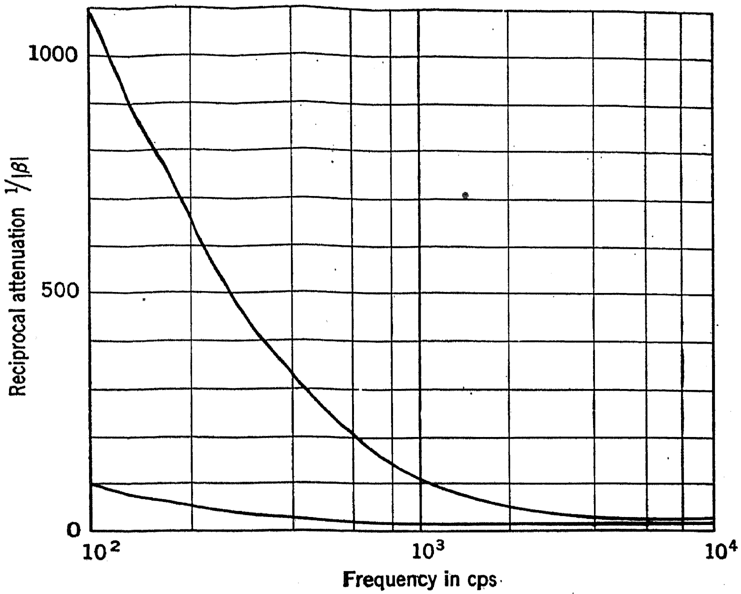


FIG. 9·9.—Attenuation with Western Electric condenser. Upper curve: load resistance 10^6 ohms, shunt capacitance 11 $\mu\mu$f. Lower curve: load resistance 10^7 ohms, shunt capacitance 1 $\mu\mu$f.

sunk holes that also serve to carry the leads. The semifinished case and ring are placed in a die and the molding operation is performed, making case, insulation, and stator electrode a single solid mechanical unit.

After it is molded, the assembly is placed in a lathe, and all interior and mating surfaces are finished in a single setup. This process ensures that the mating surfaces marked *a* in Fig. 9·10 will be truly concentric with the bushing bore and with the inner and outer surfaces of the electrodes, and that the electrode surfaces will be plane, correctly spaced, at right angles to the axis, and parallel with the mating surfaces *b*. The final operation in the case of the half that bears the sectors is to set it up on a rotary table and to mill three radial slots that cut the ring into three 120° sectors. The technique of machining all important dimensions in a single setup produces a unit with excellent over-all dimensional accuracy without having to hold extremely close dimensions on the

individual pieces, and without necessitating difficult or critical assembly operations.

The Mycalex sheet from which the rotor is formed is surface-ground on both sides to ensure flatness, parallelism, and smoothness of faces. It is then blanked out, bored, assembled between two collars on the stainless-steel shaft, and the edge is finish-machined to the shape shown in Fig. 9·8.

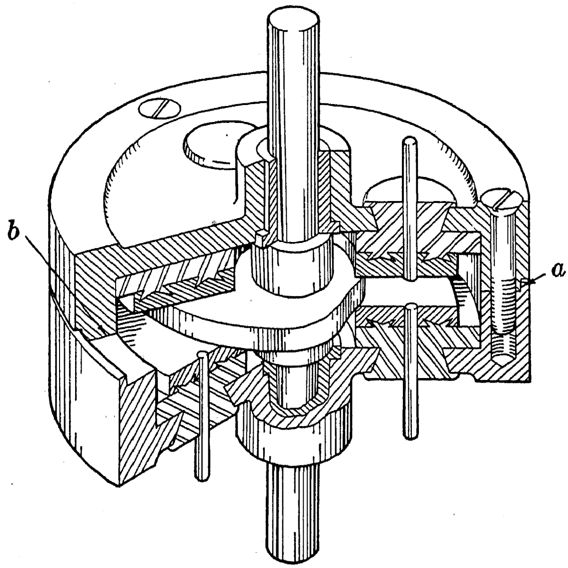


FIG. 9·10.—Nilsen condenser construction.

Both the Western Electric and the Nilsen condenser are compact, dust-tight, reasonably immune to corrosion, and uniform in characteristics, and both have proved satisfactory in the field. In operation the rotors do not turn at speeds over a few revolutions per second, nor for intervals of more than a few seconds, but their low torque and the use of Oilite bushings would permit their operation at higher speeds if necessary.

9·2. "Sweep-scanning" Condensers.—The development of the so-called "sweep-scanning" condensers was made necessary by the development of radar antennas that permitted rapid continuous scanning with a sharp beam. To take full advantage of the information furnished by such an antenna it became necessary to devise a position-data-transmitting device that would follow the antenna, and to choose repetition rates that would be compatible with the geometry of the display. The problem was complicated by the fact that the relation between the position of the radar beam and that of the shaft controlling its motion is not necessarily linear; therefore, a linear sawtooth sweep-voltage generator with only a synchronizing signal from the scanning shaft cannot

ordinarily be used. Other devices such as potentiometers, rotary inductors, etc. also have serious limitations, particularly when operated at the high speeds necessary. A major disadvantage of devices using nonlinear circuit elements is the impossibility of making static measurements on the system in order to calibrate the position of the cathode-ray beam in terms of the radar beam. The most satisfactory solution in such cases has proved to be the use of capacitive voltage dividers with the special condensers described in this section.

Figure 9·11 is a simplified block diagram showing the method of gen-

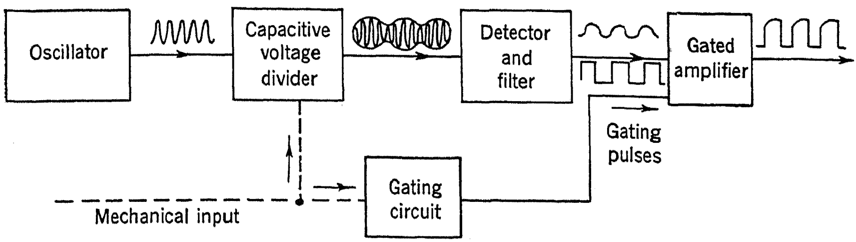


FIG. 9·11.—Generation of sweep-voltage wave.

erating sweep-voltage waves of arbitrary shapes by means of capacitive voltage dividers. An oscillator generates a constant-amplitude voltage, usually at a frequency of approximately 1 Mc/sec, which is amplitude-modulated by the voltage divider. The modulated voltage is detected and all frequencies except those necessary for satisfactory reproduction of the modulation envelope are filtered out. The envelope voltage is then passed through a gated amplifier that removes all of the envelope wave except the portions that are to be applied to the cathode-ray tube as sweep voltages. Synchronization of the motion of the cathode-ray beam and the radar beam is assured by driving both the sweep condenser of the voltage divider and the pulse-producing device in the gating circuit from the same shaft that drives the antenna rapid-scan mechanism, either directly or by means of a suitable servomechanism.

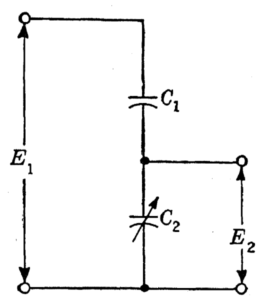


FIG. 9·12.—Simple capacitive voltage divider.

Voltage-divider Circuits.—If a constant a-c voltage E_1 is impressed across the circuit of Fig. 9·12, the output voltage E_2 across the condenser C_2 will be

$$E_2 = E_1 \frac{C_1}{C_1 + C_2} = pE_1. \tag{28}$$

If C_2 (or C_1) is a variable condenser with plates suitably shaped and if the motion of its shaft duplicates that of a radar beam, the output voltage

E_2 may be used to generate sweep voltages for the radar indicator. A simple analogue of this method would be the use of a constant d-c voltage impressed on a potentiometer, the motion of whose arm duplicates that of the beam.

Either C_2 or C_1 or both can be made variable but it is preferable in most cases to make C_2 variable. Then C_1 can be a small fixed condenser whose stray capacitance to ground will be negligible. In this case, the general equation for the capacitance of C_2 in terms of the voltage ratio $p(\theta)$ will be

$$C_2(\theta) = C_1 \frac{1 - p(\theta)}{p(\theta)}. \tag{29}$$

Here $p(\theta)$ is a function of the angle θ of the radar beam, which may or may not be a linear function of the angle of the condenser shaft. If it is not linear, the expression (29) must be modified by including the appropriate function in the $p(\theta)$.

Display systems using this method of precision data transmission usually require one of two functions of p in terms of θ. For accurate mapping it is desirable to make

$$p(\theta) = a + b\theta. \tag{30}$$

In cases where the radar antenna as a whole is to be pointed at the target it is desirable to have the central portion of the display greatly expanded to permit accurate angular settings to be made, but the peripheral portions compressed to include a sufficiently large angular range to facilitate getting on target. In such cases (and also in others) a very useful function is

$$p(\theta) = a + b \sin \theta. \tag{31}$$

In these two expressions b may be either positive or negative, but it is always smaller than a. In Eq. (31) the sine may be replaced by a cosine by a suitable shift of the zero value of θ. The r-f voltages modulated according to either Eq. (30) or Eq. (31), after rectification and filtering and with their d-c bases shifted, give control voltages proportional to θ and $\sin \theta$ respectively.

The substitution of Eqs. (30) and (31) in Eq. (29) gives, respectively,

$$C_2 = C_1 \frac{1 - a - b\theta}{a + b\theta}, \tag{32}$$

and

$$C_2 = C_1 \frac{1 - a - b \sin \theta}{a + b \sin \theta}, \tag{33}$$

from which the plate shapes of C_2 may be designed. If the mean value of p is made $\frac{1}{2}$ so that the mean value of C_2 is equal to C_1, these expressions become, respectively,

$$C_2 = C_1 \frac{1 - 2b\theta}{1 + 2b\theta}, \tag{34}$$

and

$$C_2 = C_1 \frac{1 - 2b \sin \theta}{1 + 2b \sin \theta}. \tag{35}$$

The actual calculation of the plate shapes, once the law of variation of capacitance with angle is established, depends upon a number of factors and will not be discussed here, but several examples of actual condensers will be given later in this section.

For rotor plates in the form of comparatively narrow blades, a suitable procedure is to design the stator plates on the assumption of infinitely narrow rotor plates, then to correct the resulting curve for the finite rotor-plate width, and finally to make the corrections for fringing (edge effect). This method was used in the designs of Bendix OAL-74747-1 and OAR-97130-1, as well as the Rauland CV-11. Analytical design methods are excessively laborious except in special cases, and corrections for fringing must usually be calculated graphically in any event. One factor that considerably lessens the labor involved is that the absolute value of the capacitance is relatively unimportant, because a constant factor can always be compensated for by changing C_1, and a capacitance-variation curve, corrected at comparatively few points and faired "by eye," will be sufficiently accurate for most purposes.

The input impedance of the simple voltage-divider circuit of Fig. 9·12 is a function both of the load impedance into which it works and of the capacitance of C_2. For most operating conditions the load impedance can be safely assumed to be infinite, but the variation of input capacitance may result in both amplitude and frequency modulation of the oscillator. For a modified Hartley oscillator such as is usually used as a driver, the amplitude modulation can be reduced to a negligible amount by using a plate tank circuit with a Q of 100 or more. Frequency modulation can be reduced to 10 per cent or less by using a high-C tank; however, if tuned r-f transformers are used in the sweep-generating circuit, even a small frequency shift may cause excessive amplitude modulation with consequent distortion of the sweep waveform.

One method of avoiding difficulties due to changing input impedance is the use of a push-pull voltage divider shown in Fig. 9·13. Here the admittance of the left-hand branch is given by

$$y = j\omega \frac{C_1 C_2}{C_1 + C_2}, \tag{36}$$

and a corresponding expression with the quantities primed applies to the right-hand branch. If the input admittance is to remain constant,

$$\frac{dy}{d\theta} = -\frac{dy'}{d\theta}. \tag{37}$$

Substituting the values for the y's in this equation and rearranging gives

$$\frac{C_1^2}{(C_1 + C_2)^2}\frac{dC_2}{d\theta} = -\frac{C_1'^2}{(C_1' + C_2')^2}\frac{dC_2'}{d\theta} \tag{38}$$

as the required expression. The condition for a balanced push-pull output voltage is

$$\frac{dE_2}{d\theta} = -\frac{dE_2'}{d\theta}, \tag{39}$$

from which can be obtained

$$\frac{C_1}{(C_1 + C_2)^2}\frac{dC_2}{d\theta} = -\frac{C_1'}{(C_1' + C_2')^2}\frac{dC_2'}{d\theta}. \tag{40}$$

The conditions of Eqs. (39) and (40) are identical if $C_1 = C_1'$.

The principal objection to the use of push-pull dividers is the difficulty of mechanically aligning the two variable condensers and of maintaining this alignment in the field. The problem is much less difficult, however, if it is possible to use straight-line-capacitance condensers, which can be aligned by small trimmer condensers in shunt with the variable condensers. Push-pull dividers have not been much used.

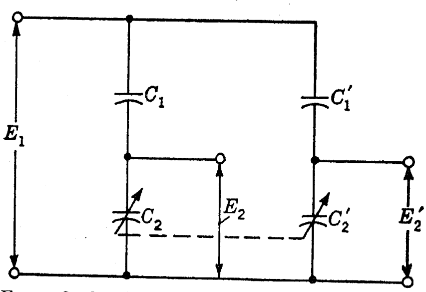


FIG. 9·13.—Push-pull capacitive voltage divider.

It is sometimes possible to compensate for nonlinear radar-beam angle vs. scanning-shaft angle characteristics by a suitable choice of network parameters. An example of this method is furnished by the voltage-divider circuits for a radar set that employed two sharp oscillating fan beams. The azimuth antenna scanned through an angle of 20° and the elevation antenna through 9°, but only 18° and 7°, respectively, were presented on the indicator tubes. The relations between beam-position and condenser-shaft angle (with the linkage actually used to drive the condenser) are shown in Fig. 9·14.

It was found that the use of a straight-line-capacitance condenser in the circuit of Fig. 9·15 would give an amplitude modulation of the

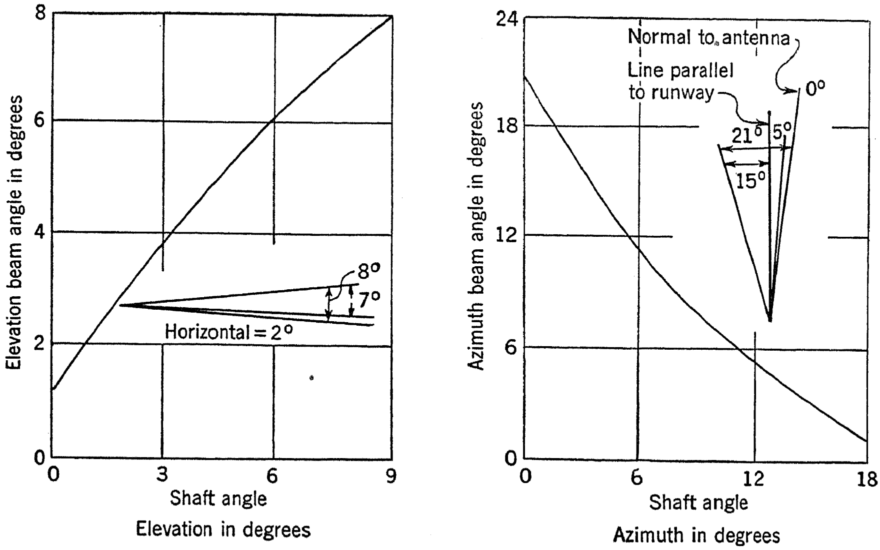


FIG. 9·14.—Beam position vs. shaft angle.

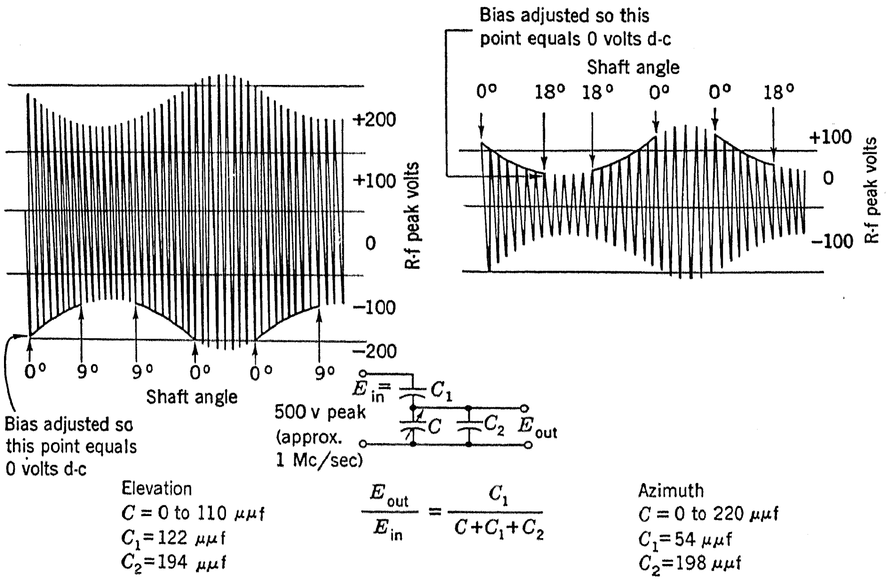


FIG. 9·15.—Voltage dividers for Fig. 9·14.

required form if the network parameters were chosen as given there. The modulated output voltages are also shown symbolically in Fig. 9·15, and the curves of output (d-c) voltage vs. condenser-shaft angle in Fig. 9·16. Comparison of these curves with those of Fig. 9·14 shows that the

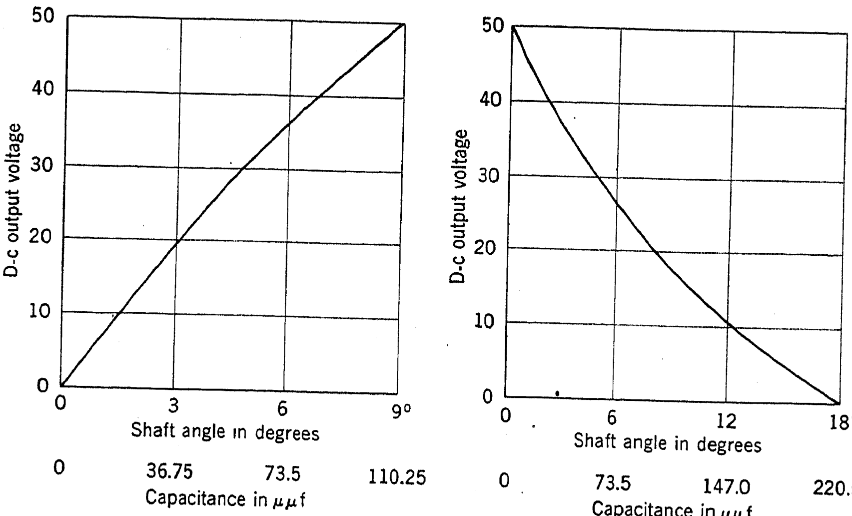


FIG. 9·16.—Performance of voltage dividers of Fig. 9·15.

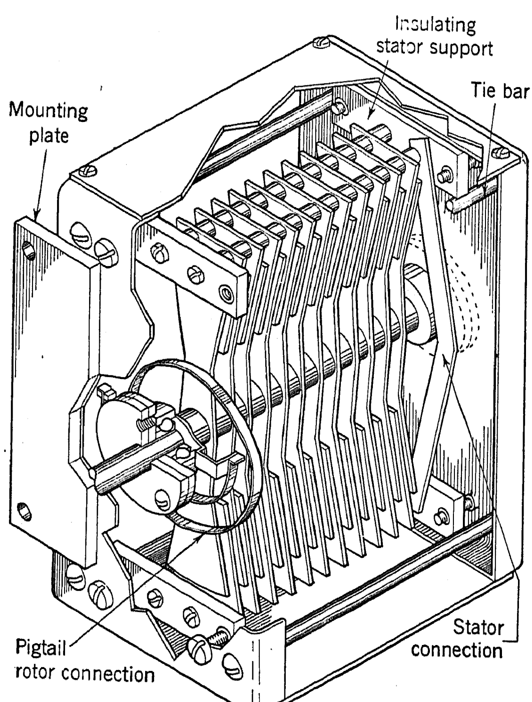


FIG. 9·17.—Bendix OAL-74747-1 sweep condenser.

approximations used are accurate, and the performance of this system in the field has been very good.

Since the ranges of variation of the variable condensers used in the two cases just discussed were chosen to be in the ratio of 2 to 1, and since the condenser shaft was required to oscillate rapidly over a limited angle because of the nature of the drive, it was found convenient to use a condenser with a balanced rotor and two identical insulated stators,

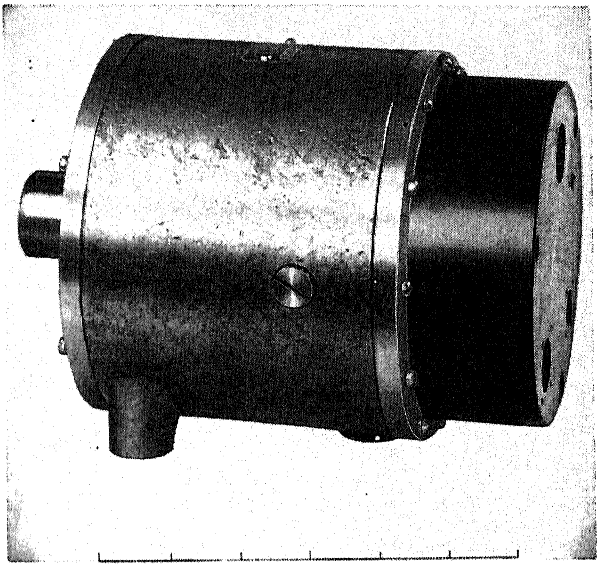


FIG. 9·18.—Rauland CV-11 condenser.

and to ground the rotor through a spring "pigtail" instead of depending upon friction contacts. For the azimuth system, which required the larger capacitance variation, both stators were used, whereas only one was connected in the elevation system. Identical condensers could therefore be used in both systems. Figure 9·17 shows the construction of this condenser.

Commercial Linear-sweep Condensers.—Besides the Bendix OAL-74747-1 condenser, there are in production two other sweep condensers that are intended to generate linear-sweep waves [according to Eq. (30)] when used in the circuit of Fig. 9·12. These are the Rauland CV-11 and the Bendix OAR-97130-1. The CV-11 is shown in Figs. 9·18 and 9·19, and the shapes of the rotor and stator plates of both are shown in Fig. 9·20. The Bendix condenser is packaged similarly to the Rauland unit and is like it in general construction but is somewhat shorter and greater in diameter.

The actual construction of the Rauland condenser deserves some

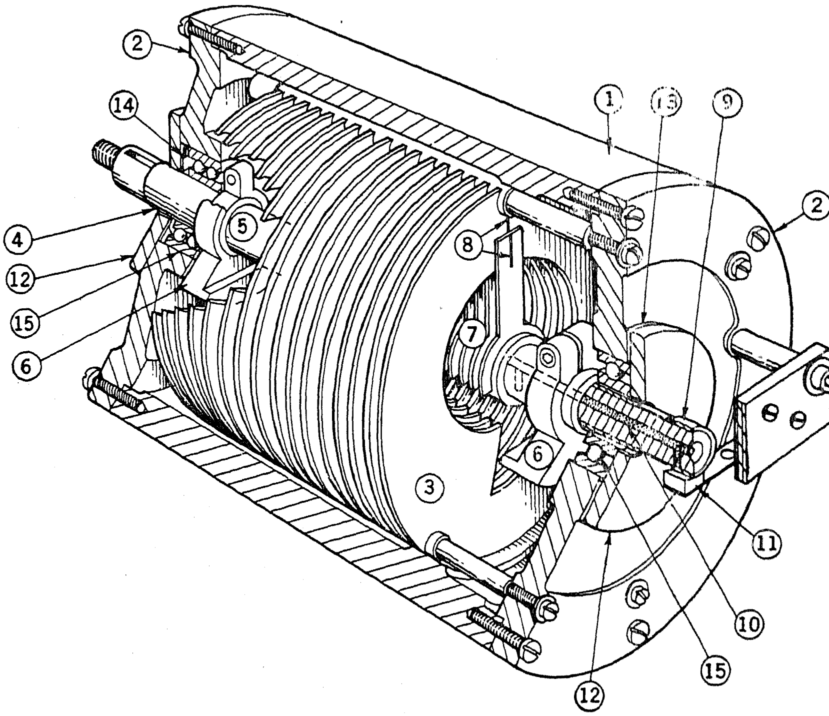


FIG. 9·19.—Construction of Rauland CV-11 condenser. (1) Housing; (2) end plates; (3) stator-plate assembly; (4) stub steel driving shaft; (5) ceramic main shaft; (6) counterweights; (7) rotor-plate assembly; (8) index marks for zeroing rotor; (9) slip ring; (10) solder connection from slip ring to stator plates; (11) brush; (12) bearing retainer plates; (13) shims for longitudinal rotor position adjustment; (14) loading spring; (15) ball bearings.

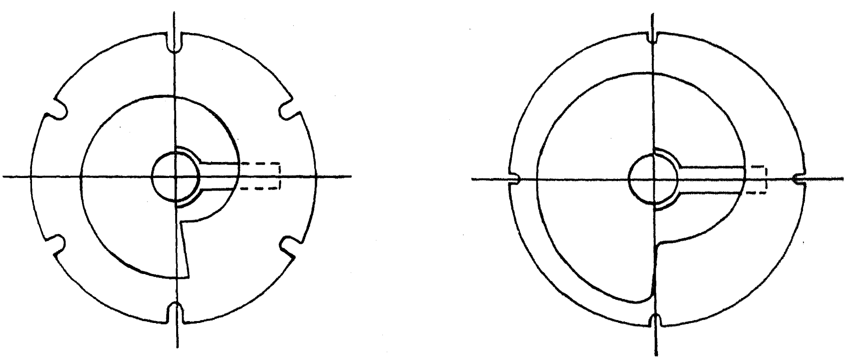


FIG. 9·20.—Plate shapes of CV-11 and OAR-97130-1 condensers.

comment because it represents good practice in the design of precision equipment. In general the CV-11 conforms to the standard Navy specifications as to material, workmanship, and resistance to temperature and humidity tests, salt-spray corrosion tests, vibration, shock, etc.

The case of the unit consists of a heavy cast Monel-metal body to which are screwed two cast end plates, also of Monel metal. The 17 stator plates, of 0.040-in. planished Monel sheet, are mounted in grooves in six mounting posts to which they are soldered after assembly. The stator plate assembly is held concentric with the cylindrical body by an internal ridge in the body, and is aligned longitudinally by being screwed to a machined surface on the front end plate. The rotor-plate assembly is similarly constructed, and is mounted on a ceramic shaft that also carries a stub steel driving shaft, two counterweights, a bearing collar, and a silver slip ring to which contact is made by a pair of silver-graphite brushes mounted outside the front end plate. This method of mounting the rotor plates on an insulating shaft is expensive but greatly improves the performance of the unit by keeping the bearings, counterweights, and stub shaft at ground potential and by making the rotor connection through the brushes and slip ring instead of through the bearings. The metal rotating parts are soldered to metallized surfaces on the ceramic shaft, and connection is made from the rotor-plate assembly to the slip ring by solder fillings in radial and axial holes in the shaft, as shown in Fig. 9·18. The light sheet-metal cover for the brush assembly was a temporary arrangement; in a service model it would be replaced by a heavier waterproof cover and all joints would be gasketed and sealed. Both rotor- and stator-plate assemblies are aligned longitudinally from the front end plate, and the rotor position is adjusted by shimming the front bearing retainer plate. End play is removed and differential expansion is allowed for by a loading spring under the rear bearing.

Specifications for Linear-sweep Condensers.—The dimensional and performance specifications may be briefly summarized in the following way. The condenser is to operate continuously in one direction to furnish a capacitance variation that agrees with the specified curve (given in Fig. 9·21 for both the CV-11 and the Bendix OAR-97130-1 units) within $\pm\frac{1}{4}$ per cent for not less than 320° of a complete rotation and that returns to its orginal value in not over 40° of a complete rotation. The capacitance tolerance holds for all tests except the temperature test. For the temperature test, the temperature coefficient is to be not more than $100 \times 10^{-6}/°C$. The condenser must operate satisfactorily over a temperature range of $-40°$ to $+70°C$, and in air of 95 per cent relative humidity at 45°C. It must withstand the standard Navy salt-spray, vibration, and shock tests. It must also withstand the continuous application of 400 volts a-c at 60 cps at any of the above temperatures and humidities, and the application of 1000 volts for 1 min immediately after the humidity test. Within 30 min of the humidity test, its leakage resistance must be not less than 10 megohms. The condenser must be capable of continuous rotation for 10,000 hr at speeds up to 2000 rpm,

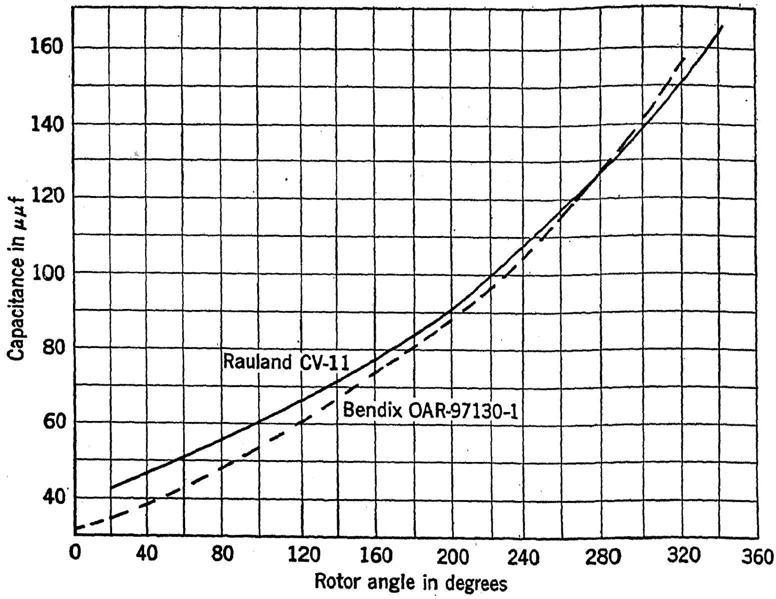


FIG. 9·21.—Capacitance vs. rotor angle.

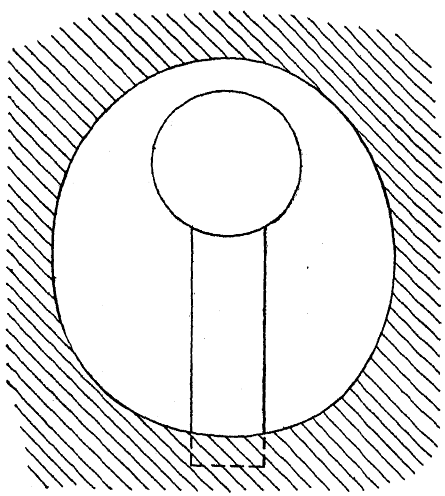


FIG. 9·22.—Plate shapes for sinusoidal sweep condenser.

and must withstand an accelerated life test of 1000 hr at 3000 rpm at 20° to 30°C and 50 to 70 per cent relative humidity. The maximum allowable torque is 4 oz-in. at normal temperatures and 8 oz-in. after 8 hr at −40°C.

The center-to-center spacing of the 17 rotor and 17 stator plates is to

be 0.160 ± 0.001 in., and the plates of each set are to be parallel within 0.001-in. total indicator reading. The tolerances on the concentricity between rotor-blade tips and stator-plate peripheries and on the parallelism between rotor and stator plates are 0.002 in. max. Longitudinal centering is to be done by setting the rotor in its maximum-capacitance position and adjusting the rotor longitudinally for minimum capacitance.

No condensers have been put into production for the sinusoidal characteristic of Eq. (31), but Fig. 9·22 gives the plate shapes for such a condenser. One reason that such condensers have not been made is that the Cardwell KS-8534 condenser of Sec. 9·1 is suitable for many such applications; another is that synchros can often be used to generate sinusoidal sweeps. Detailed information regarding the generation of sweep waveforms of arbitrary shapes and their application to cathode-ray tubes will be found in Vols. 19 and 22 of the Radiation Laboratory Series.

CHAPTER 10

ROTARY INDUCTORS

By W. F. Goodell, Jr.

10·1. Introduction.—A rotary inductor, as the term is used in this chapter, is a device in which the coupling between one or more stator coils and one or more "rotor" coils can be varied by the rotation of a shaft. In certain forms of rotary inductors the so-called "rotor" coils do not rotate although the variation of coupling still takes place when the shaft is rotated. These devices may be used to transmit angular information or torque to remote points, to modulate an electrical signal with mechanical information, or to demodulate an electrical signal, presenting the modulating information in electrical or mechanical form. Power-handling capacities of the different types and sizes of units range from milliwatts to kilowatts, and the torque-transmitting capacities from milligram-millimeters to hundreds of pound-feet. Because few applications require large power-handling capacity, most of the units discussed here are those whose capacity is a few hundred watts or less and whose output torque is of the order of a few inch-ounces.

In the following discussion, units have been primarily classified according to their construction and basic principles of operation, as synchros, Magnesyns, and Telegons. Synchros have been further classified according to the most common use of the particular unit, for example, the transmission of torque or position or the electrical modulation of a timing wave.

SYNCHROS

10·2. Nomenclature.—"Synchro" is a generic term used by the Navy to describe a rotary inductor similar to an induction regulator, in which variable coupling is obtained by changing the relative orientation of the primary and secondary windings. The primary windings, from one to three in number, are normally wound upon a rotor of laminated magnetic material. The secondary windings, from one to three in number, are normally wound on a slotted stator of magnetic material. The rotor may have only limited rotation, in which case the connections to the primary windings are brought out on flexible leads, but usually it is free to rotate continuously and the connections are brought out by slip rings and brushes. Although all Navy standardized units are known as "syn-

chros," manufacturers have designated their particular units by trade names such as "Selsyn" for the General Electric Company, "Autosyn" for the Bendix Aviation Corporation, "Teletorque" for the Kollsman Instrument Company, and "Diehlsyn" for the Diehl Manufacturing Company. A representative group of synchros is shown in Fig. 10·1.

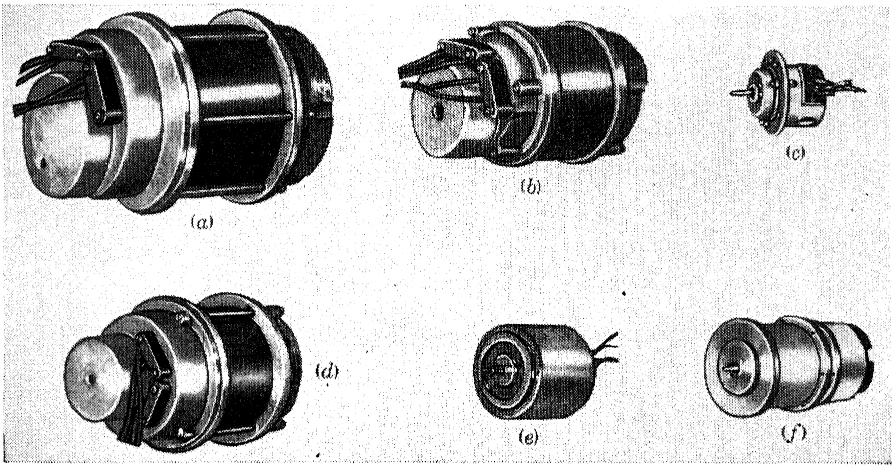


FIG. 10·1.—Typical synchros. (*a*) Size 7 synchro; (*b*) Size 5 synchro; (*c*) Pioneer AY-series Autosyn; (*d*) Size 6 synchro; (*e*) Diehl Frame B173185 synchro; (*f*) Size 1 synchro.

Probably the most common use of synchros is the transmission of angular data or torque by the use of two such units back-to-back or in conjunction with a servo system. Other uses include modulation of electrical waveforms, resolution of vectors into components, and combination of vectors in various computing devices.

The nomenclature of synchros is further complicated by the different designations given the same functional types of units by the Army and Navy. For purposes of simplification the Navy nomenclature will be used here. The Army equivalent nomenclature is given in Table 10·1.

TABLE 10·1.—SYNCHRO FUNCTIONAL CLASSIFICATION

Navy term	Navy symbol	Army term	Army symbol
Synchro generator	G	Transmitter	TR
Synchro motor	none (see text)	Repeater	RP
Synchro control transformer	CT	Transformer	CT
Synchro differential generator	DG	Differential transmitter	DT
Synchro differential motor	D	Differential repeater	DR

A standard Navy synchro would be designated by a symbol such as 5HCT Mark 2 Mod 3B, where the various digits have the following significance:

1. The initial number indicates the size group to which the unit belongs. Standard Navy synchros fall naturally into six distinct groups, according to Table 10·2. Because of the convenience of this method of designating size, other synchros such as Army units and GE Selsyns are often referred to as "Size 1" or "Size 5" if they approximate the corresponding Navy type.

TABLE 10·2.—SYNCHRO SIZES AND WEIGHTS

Size	Approx. weight, lb.	Approx. length, in.	Approx. diameter, in.
1	2	3.9	2.95
3*	3	5.2	3.10
5	5	6 to 6.8	3.4–3.6
6	8	6.4–7.5	4.5
7	18	8.9–9.2	5.75
8*	60	13.13	8.63

* Sizes 3 and 8 are seldom used.

2. One or more modifying letters may follow the numeral. In the example above, the H indicates that the unit is fitted with special bearings and brushes to permit high-speed operation. Other modifying letters are the mounting designations F, N, and B, which designate flange-, nozzle-, or bearing-mounted (see below), and S, which indicates that the unit is special in some way and may not be interchangeable with other units with the same designation but with a different "Mod" number.
3. After the modifying letters, if any, come the letters designating the function of the unit, according to Table 10·1. In the case of a motor, for which no symbol exists, the mounting designation letter is used: thus a 1F, a 5N, and a 6B would all be standard motors without any special features. Since units with N or B mountings are relatively uncommon, F has come to be practically a synonym for motor. For the same reason the F is usually omitted in the designations of units other than motors.
4. The "Mark" number is actually a type designation: all standard synchros of the same symbol and Mark number are interchangeable.
5. The "Mod" (model, or modification) number designates the manufacturer, according to Table 10·3.

All replaceable parts of a given synchro will interchange with those of any other synchro of the same type, Mark, and model. When a manufacturer makes minor improvements on a synchro the improved units bear a letter after the Mod number: thus a Mod 3B unit would interchange with a corresponding Mod 3 unit, but the parts of the two would not necessarily interchange since the two do not have the same Mod number.

TABLE 10·3.—MANUFACTURERS OF STANDARD NAVY SYNCHROS

Model	Manufacturer
1	Arma Corporation, Brooklyn, N. Y.
2	General Electric Company, Schenectady, N. Y.
3	Ford Instrument Company, Long Island City, N. Y.
4	Bendix Aviation Corp., Marine Division, Brooklyn, N. Y.
5	Control Instrument Company, Brooklyn, N. Y.
6	Diehl Manufacturing Company, Finderne, N. J.
7	Bennel Machine Company

The Navy nomenclature is somewhat involved but it is practical. The Army designates its units by Roman numerals assigned in order of adoption of the units by the Ordnance Department. If minor modifications in shaft-end or mounting details are made, an Arabic numeral is added to the designation. Thus the Army designation is entirely arbitrary and is useless in determining the function, size, or manufacturer of a unit.

The nomenclature used by the General Electric Company for its Selsyn units is as follows. All designations start with "2J" which indicates that the unit is listed under the GE catalog subdivision 2J, which covers Selsyn units. After the 2J, a D may appear; if present, it indicates that the unit is provided with a damping disc to permit operation as a motor. Units without the D must be geared to a driving mechanism. Following the D is a number denoting size, using the Navy system of Table 10·2. A letter following the size number indicates the shaft and frame type, and a final number designates the serial number of the electrical design of the unit using that particular set of mechanical parts. Thus a 2JD5H1 would be a Size 5 synchro motor with an H-type mechanical design and the first electrical design in the 5H frame.

Most other manufacturers designate their units numerically. Pioneer-Bendix prefixes the letters "AY" to the type number to indicate that the unit is a synchro or "Autosyn," and Diehl uses "FJ" or "FJE," except in the case of the FPE-43-1, a Diehl synchro which was incorrectly designated.

10·3. Definitions. *Synchro Generator.*—A unit the rotor of which is mechanically driven, for generating or transmitting electrical signals corresponding to the angular position of the rotor.

Synchro Motor.—A unit the rotor of which is free to turn in accordance with the electrical signals received.

Synchro Differential Generator.—A unit the rotor of which is mechanically driven, for modifying a received signal and transmitting an electrical signal corresponding to the sum or difference of the impressed and modifying signals.

Synchro Differential Motor.—A unit the rotor of which is free to turn in accordance with the sum or difference of electrical signals received from two sources.

Synchro Control Transformer.—A unit which is normally used to produce a single-phase voltage whose magnitude is proportional to the sine of the angle of rotation of its rotor with respect to the magnetic field of its stator.

Synchro Capacitor.—A unit whose function is to counteract the lagging component of the exciting current drawn by a differential unit or a control transformer, thereby reducing the heating of the rotors of the synchro generator and also improving the stiffness of the system.

In the interests of brevity, when it is not required to prevent ambiguity, the word "synchro" will frequently be omitted from these designations throughout the remainder of this chapter.

10·4. Theory and Construction of Units.—The structure of most synchros is similar to that of a conventional 3-phase alternator in a fractional-horsepower size.

Stators.—Generally speaking, the stator of a synchro is a cylindrical slotted laminated magnetic structure usually bearing a 3-phase Y-connected winding which is (with the exception of differentials and control transformers) the secondary of the synchro. In most cases the stator laminations are skewed one slot pitch to eliminate slot-lock and the resulting angular errors. In units in which the stator laminations are not skewed, the rotor laminations are skewed instead.

The stator winding is not 3-phase in the usual meaning of the term since all induced voltages are in time phase. The three legs of the stator winding are spatially displaced 120° from each other.

Rotors.—The standard types of synchros are of two-pole rotor construction. Three types of rotors are employed, and are illustrated in Fig. 10·2.

The salient-pole rotor, shown in Fig. 10·2*a*, is the most common type of synchro rotor. This is also known as the "dumbbell" or "H" type and is used in synchro generators and motors. It bears a machine-wound single-phase spool winding which serves as the primary or excitation winding of the synchro. Only two slip rings are required for this unit, and it should be noted that they have the full excitation voltage impressed upon them at all times.

The umbrella rotor, shown in Fig. 10·2*b*, has been used in some control transformers. This is an intermediate design and may be considered a modification of the salient-pole design.

The third type of rotor is the cylindrical or drum type, and is shown

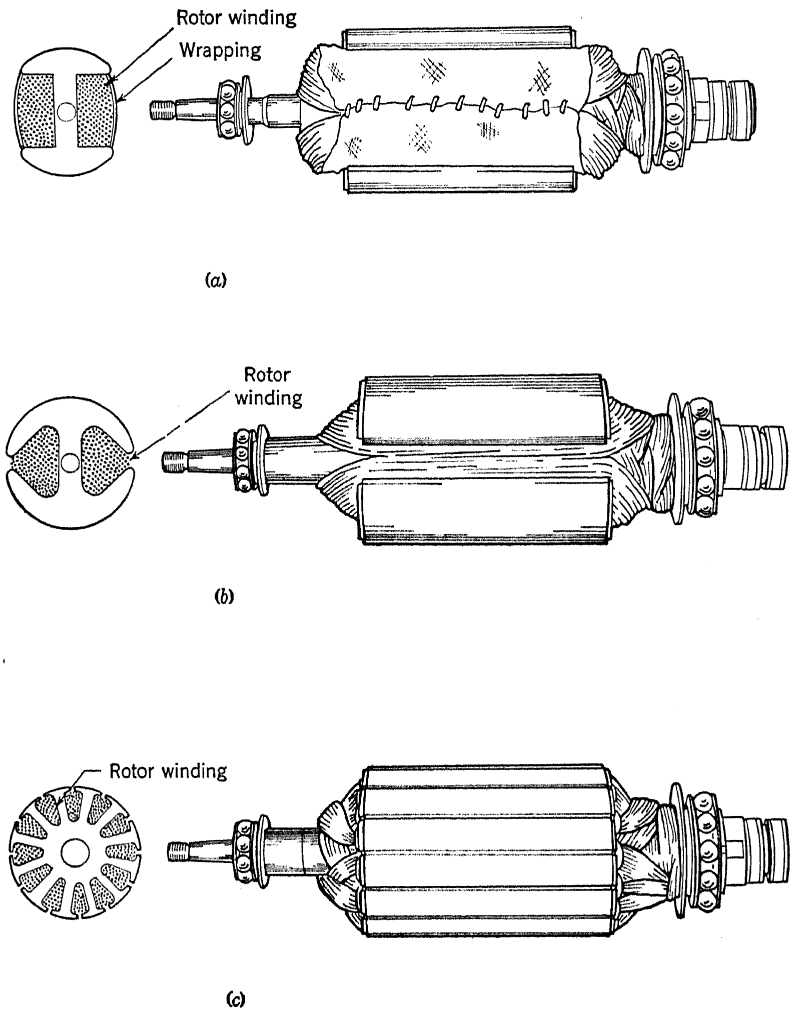


FIG. 10·2.—Synchro rotors. (*a*) Dumbbell; (*b*) umbrella; (*c*) drum or wound.

in Fig. 10·2*c*. These are commonly called wound rotors and are slotted and laminated structures carrying either a single-phase winding with two collector rings for control transformers or a Y-connected 3-phase winding with three collector rings for differential units.

Synchro Generators.—In the conventional synchro generator, single-phase a-c excitation is applied to the winding of a dumbbell rotor. The exciting current flowing in this primary winding produces a flux which links each of the three stator (secondary) windings to a greater or lesser degree depending upon the angular position of the rotor with respect to the several stator windings. Figure 10·3 shows the induced secondary

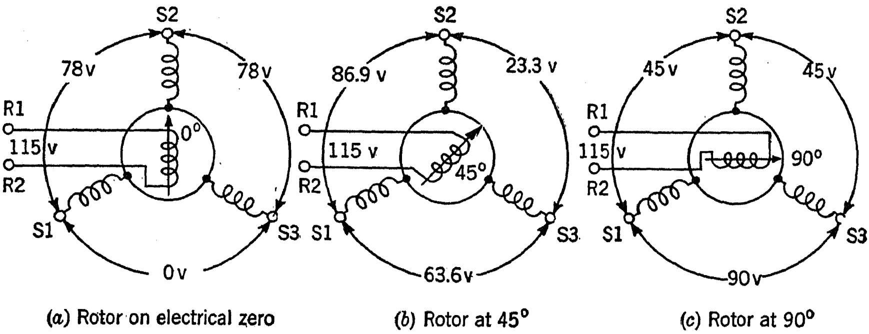


FIG. 10·3.—Induced voltages in synchro-generator stator. (NOTE: rotation is reversed from Navy standard, which specifies counterclockwise rotation for increasing quantities.)

line voltages for three different positions of the rotor. These induced voltages may be represented as $V \sin \alpha$, $V \sin (\alpha - 120°)$, and $V \sin (\alpha - 240°)$, where V is the rated secondary voltage and α is the angular displacement of the rotor from its electrical zero position. A plot of these voltages as functions of α is shown in Fig. 10·4.

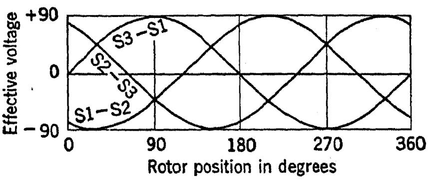


FIG. 10·4.—Navy synchro stator voltages.

For a given distribution and polarity of stator voltages, there is but one corresponding position of the rotor, and conversely, for any position of the rotor there is but one secondary-voltage condition. Thus the stator voltages constitute an electrical indication of the rotor position. A typical synchro generator is shown in Fig. 10·5.

Synchro Motors.—Electrically, a synchro motor is identical with a synchro generator, and the preceding discussion applies. The distinguishing feature of a synchro motor is that near one end of the rotor shaft there is an oscillation damper, a flywheel with about the same moment of inertia as that of the rotor itself, which is free to rotate on the shaft. A friction coupling between the rotor and the shaft provides a means for transferring energy from the rotor to the disk, and stops limit to about 45° the free rotation of the flywheel relative to the shaft. This friction coupling dissipates energy when the rotor oscillates, as it does when

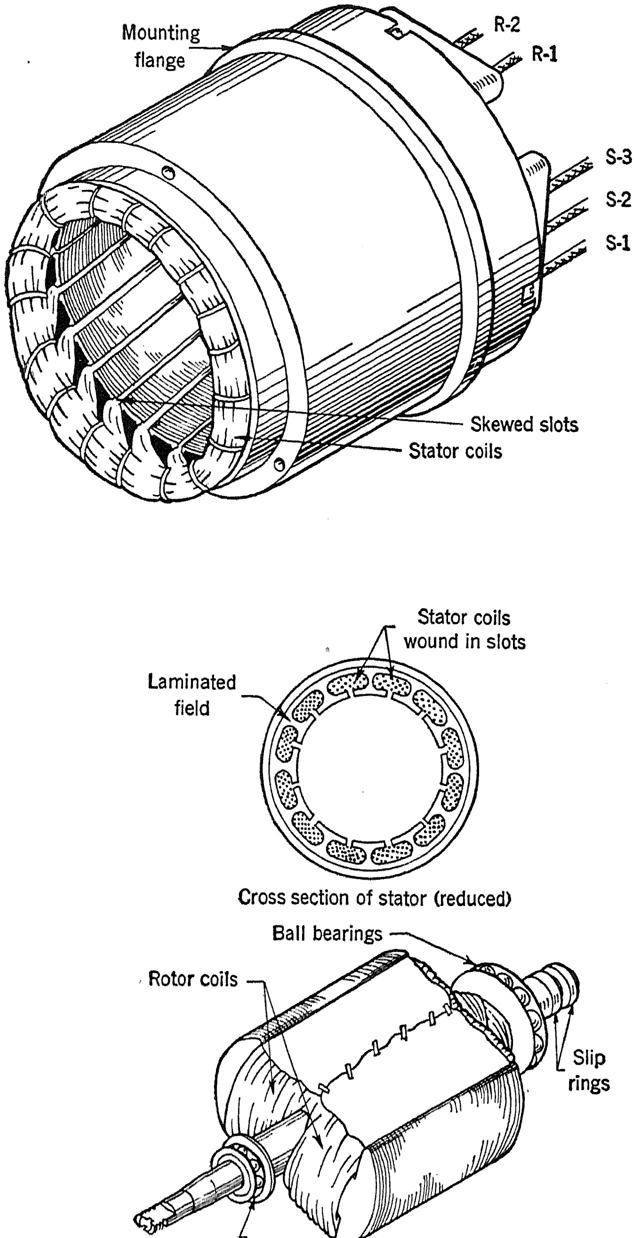


Fig. 10·5.—Synchro generator.

coming into the synchronous position.[1] The added inertia furnished by the oscillation damper prevents the motor from "running away," an inherent danger in either synchro motors or differentials. The damper is illustrated in Fig. 10·6.

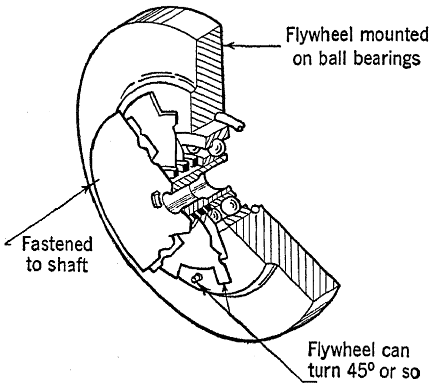


FIG. 10·6.—Synchro-motor damping flywheel.

"Running away" of a synchro motor is not the same phenomenon as that associated with the high speed attained by a series motor on removal of the load, but arises from the similarity of a synchro unit to a single-phase induction motor. The currents in the stator are approximately in the same time phase and so produce a magnetic field constant in direction. There is, of course, a primary magnetic field due to the rotor current. This is the same situation that exists in the single-phase induction motor, and, like this induction motor, the synchro unit has no starting torque. When the synchro generator drives a synchro motor or a differential at low angular velocities, the motor torque developed is not great enough to overcome the synchronizing torque, and the units remain in step. If the angular velocity becomes large, however, the motor torque becomes sufficiently great to overcome the synchronizing torque, and the synchro generator no longer has control. The effect of the inertia and dissipation added by the damping flywheel is to prevent momentary oscillatory velocities greater than the critical value.

Obviously, a synchro motor can be used as a synchro generator but the converse is not true for 60-cps units. Generally speaking, synchro motors designed for 400-cps application have little tendency to run away and so are not provided with dampers.

Differential Units.—Differential machines are wound with 3-phase Y-connected windings on both rotor and stator; the rotor is a slotted cylindrical structure.

A 60-cps differential machine is usually connected between two salient-pole synchros. The stator winding is the primary and derives its magnetizing current from the stator of a connected synchro generator. The three line voltages of the synchro generator give rise to proportional currents in the 3-phase stator windings of the differential machine. The

[1] Although commonly used, "synchronism" is perhaps not correct in its application to synchros, since no notion of time is involved. Two synchros are in synchronism when their unbalance voltages are minimized by placing their rotors in corresponding positions.

resultant magnetic flux produced by these currents in the differential stator is in the same position with respect to the stator winding as the exciting flux in the generator is with respect to its stator winding. Thus, there is produced in the differential machine a flux whose position corresponds to the position of the synchro-generator rotor.

As was the case with the synchro generator, this flux induces in the secondary windings of the differential, voltages whose magnitudes are dependent upon the relative positions of the windings and the flux. It follows that the distribution and polarity of the voltages induced in the secondary of the differential machine represent the algebraic sum of the rotations of the rotors of the synchro generator and the differential with respect to their stators.

The differential generator obtains its excitation from the other units of the system to which it is connected, and since it has losses it is evident that to have 90-volt primary (stator) windings supply 90 volts on the secondary (rotor) windings, the units cannot be wound on a 1/1 turn ratio, but on a 1/1-plus basis. For this reason the stator is always considered the primary and should be connected to the stator windings of its associated synchro generator.

This machine can be used either as a differential generator for superimposing a correction on the signal from a synchro generator, or as a differential motor for indicating the sum or difference of rotation of two separate synchro generators. In the latter case, it is equipped with a mechanical damper, as explained in the above discussion of synchro motors. A typical synchro differential is illustrated in Fig. 10·7.

Synchro Control Transformers.—The control transformer is equipped with a single-phase winding on a cylindrical rotor. In this machine, as in the differential machine, the stator constitutes the primary winding, receiving excitation from a synchro generator. Also, as in the differential machine, the exciting currents produce a resultant flux in the machine, the position of which, with respect to the stator, corresponds to the angle represented by the applied stator voltages. This flux induces in the rotor winding a voltage whose magnitude is dependent upon the position of the rotor with respect to the flux. If the rotor is in such a position as to link a maximum of the flux, the induced voltage is a maximum; a 90° displacement will place the rotor coil across the flux and the induced voltage will be zero. The latter position (often called the "null" position) is the normal condition of operation of a control transformer.

It is apparent that there are two positions of the rotor at which zero voltage will be induced; but a slight rotation of the rotor in the clockwise direction, for example, will produce a small voltage whose polarity depends upon which of the two null positions is chosen. Thus, if means are provided for recognizing polarity, there is but one "correspondence"

position of a control transformer for a given distribution of exciting voltages. For a further discussion of this matter see the instructions for "zeroing" a control transformer in Sec. 10·10.

Conceivably, a machine with a dumbbell rotor could be used to give control-transformer action. Because of the fringing at the pole tips,

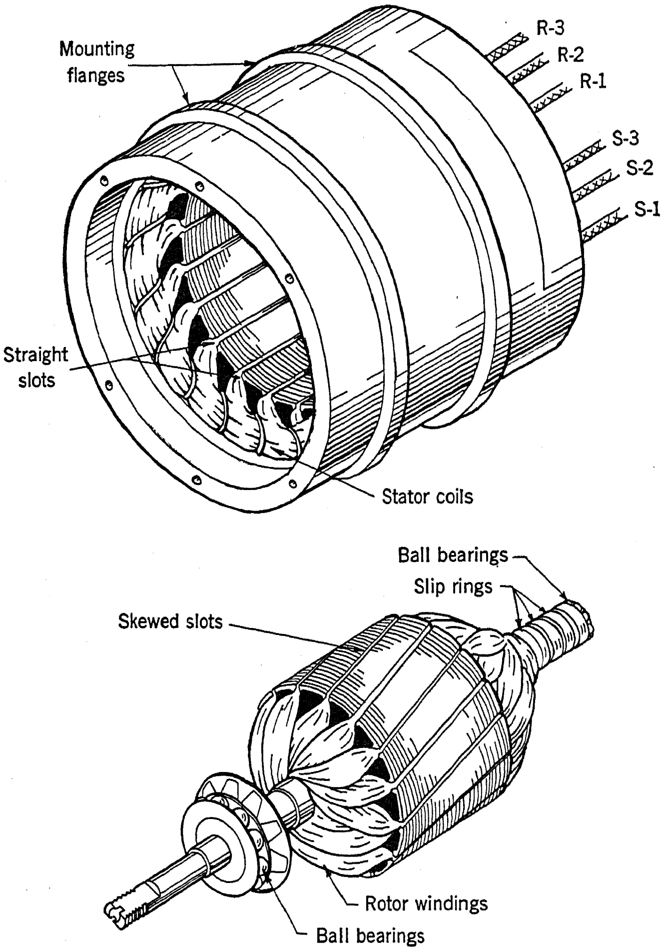


FIG. 10·7.—Synchro differential.

however, the zero position would not be accurately defined, and, because the rotor axis is displaced 90° from the axis of the exciting flux, this flux would meet a very large air gap and the magnetizing current would be prohibitively high. The input impedance to the control transformer would therefore vary with rotor position. This variation would introduce additional errors into the data-transmission system.

The impedances of the stator and rotor windings of a control transformer are considerably higher than those of an equivalent-sized synchro generator or motor and a control transformer should never be used to feed a low-impedance load. High impedance of the stator winding reduces the excitation current drawn from the system by the addition of

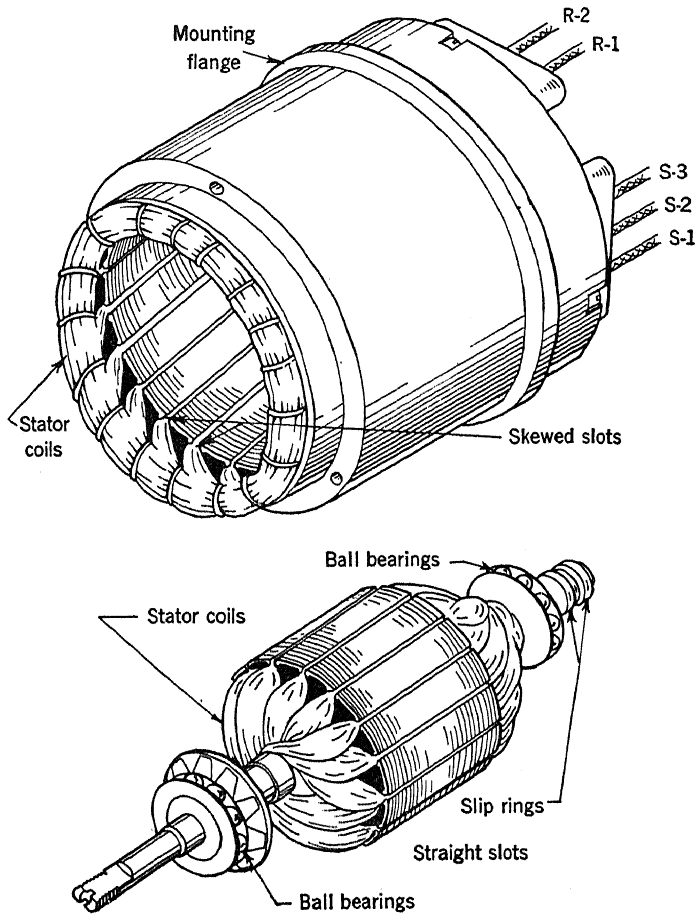


FIG. 10·8.—Synchro control transformer.

the control transformer, and high impedance of the rotor winding gives a higher and more useful output-voltage gradient. A typical control transformer is shown in Fig. 10·8.

Synchro Control Motors.—There are a great many possible variations in the mechanical and electrical details of synchros. One of the most useful modifications of a synchro is the "B" or bearing-mounted machine. Here the rotor and the stator may be rotated independently. The usual

type is the synchro control motor, which is identical to a standard synchro motor except that the whole machine is rotatable. Control transformers are also frequently mounted in this same fashion. The

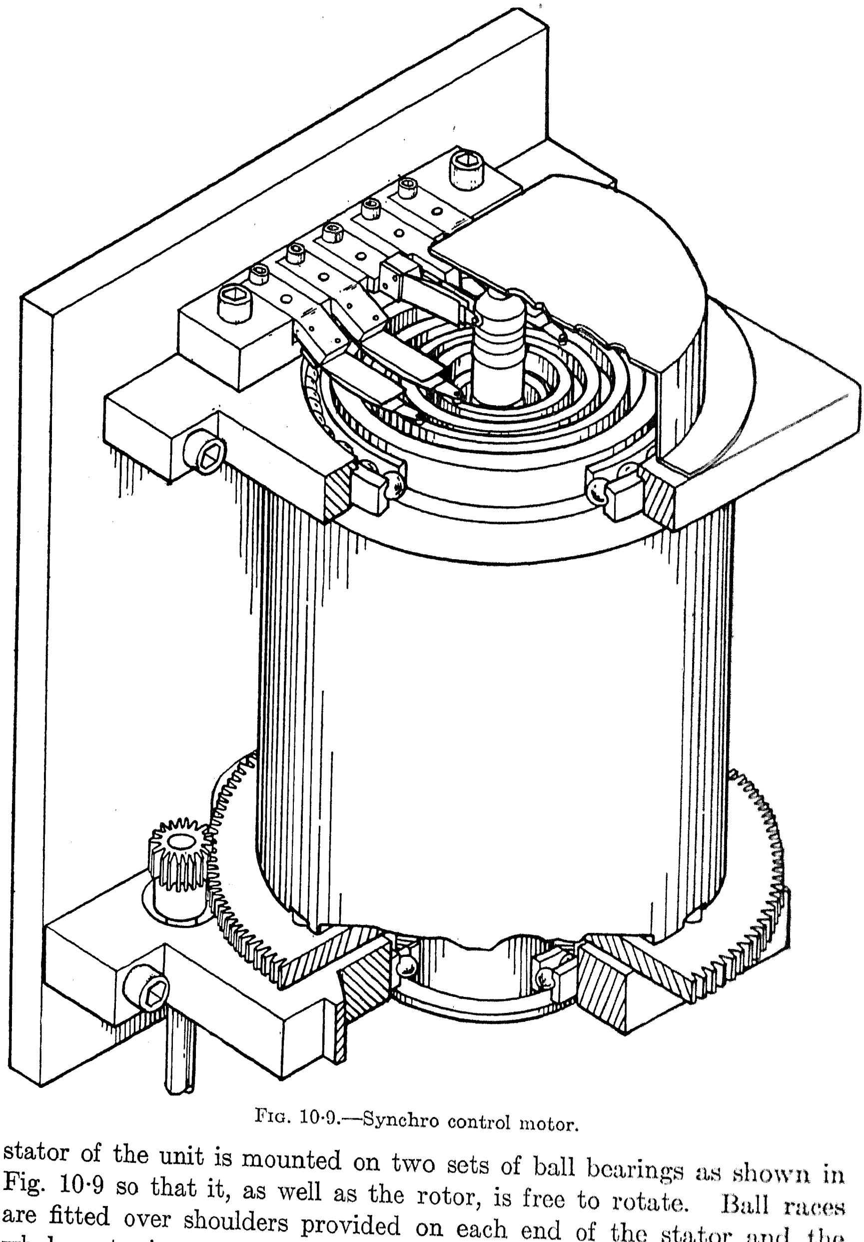


FIG. 10·9.—Synchro control motor.

stator of the unit is mounted on two sets of ball bearings as shown in Fig. 10·9 so that it, as well as the rotor, is free to rotate. Ball races are fitted over shoulders provided on each end of the stator and the whole motor is supported on hangers. To allow connections to the three

stator leads, three additional slip rings are provided. They are mounted on the end of the stator opposite the shaft extension. With this arrangement the position of the rotor with respect to the stator is determined by the voltages applied to the five leads, as is the case with any synchro motor. The position of the stator with respect to its mounting is usually set by means of a worm or pinion which drives a gear on the stator. This gives an action equivalent to that of the differential generator without the loss of accuracy which the insertion of such a unit ordinarily involves.

Reversed Synchros.—Higher torques can be obtained from synchros if the magnetizing power is increased. In conventional synchro generators and motors the magnetizing power is applied to the rotor windings and the heat produced by the rotor copper and iron losses must be dissipated through the air gap to the stator and thence to the surrounding air. For a given temperature rise the allowable input power may be increased if excitation is applied to the stator instead of the rotor. The change in torques obtainable is dependent upon the resistance-reactance ratio of the windings. Such modified machines are known as reversed synchros, and are exemplified by the types "A" and "M" Autosyns built by the Marine Division of Bendix Aviation Corporation, the type 15-021 synchro generator and the type 15-022 synchro motor built by Henschel, the type FJE-65-4 built by Diehl, and several commercial General Electric Selsyns.

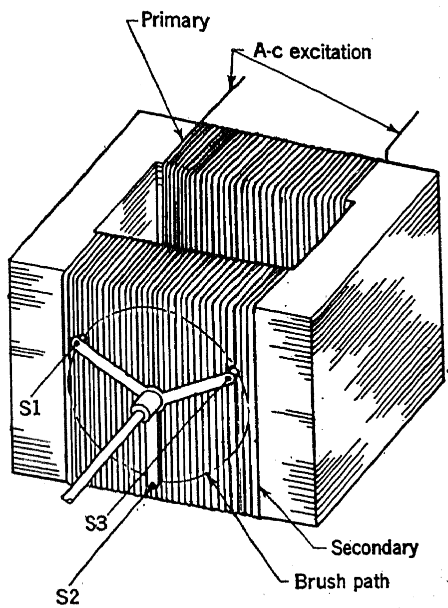


FIG. 10·10.—A-c commutator transmitter.

The chief disadvantage of this type of synchro is that the secondary unbalance currents, which are very small for rotor positions near the null, must pass through slip rings and brushes. These components may become dusty or dirty and offer a high resistance to the currents. Since the unbalance voltages are so low, they may not be able to burn through this grime, in which case the accuracy and smoothness of operation of the associated synchro system will suffer.

The A-c Commutator Transmitter.—Another device which may be discussed here, (although strictly speaking it is not a synchro), is the a-c

commutator transmitter shown in Fig. 10·10. This device is simply a transformer with a single-layer secondary, on the flat side of which there is a bare circular path on which three brushes spaced 120° apart around a common shaft make contact with the secondary winding. The action is analogous to that of a General Radio Variac, or to one of the sine-cosine potentiometers described in Chap. 8. The commutator transmitter has not been extensively used, but possesses certain advantages over a synchro generator, especially in the larger sizes. If the pitch of the secondary winding is uniform and sufficiently fine to avoid trouble from "graininess," the accuracy should be better than that of a synchro generator since there

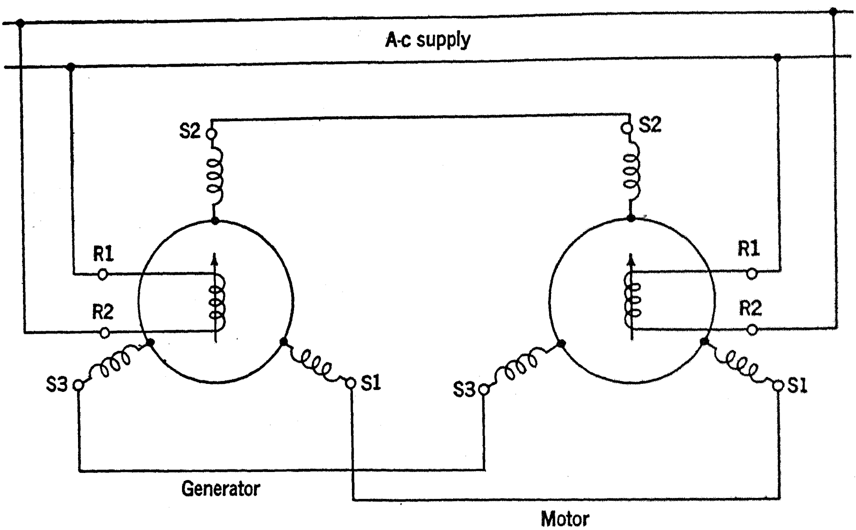


FIG. 10·11.—Synchro generator-motor system.

is no possibility of mechanical reaction from the load back to the transmitter shaft. Also, since there is no air gap, the coupling coefficient between primary and secondary can be made appreciably higher than is possible with a synchro. It would seem that a properly designed commutator transformer might be useful as a driver for cathode-ray-tube deflection yokes (see Sec. 10·14).

10·5. Common Synchro Systems. *Synchro Generator and Motor.*—It has been shown that for a given position of a synchro-generator rotor there is a given distribution of single-phase voltages between the three stator leads; the same holds true for a synchro motor. If the two stators are interconnected, as in Fig. 10·11, and if the rotors are in identical positions, the stator voltages will balance and no current will flow in the stator windings. If, however, the rotors are displaced with respect to each other, then the stator voltages will not be matched and the net

unbalanced voltages will cause current to flow in the stator windings. These currents will create torques in both machines, and the motor rotor, being unrestrained, will move to a position of synchronism with the generator. Note that the synchro motor is not a "motor" in the usual sense of the word: the mechanical work done by the synchro motor is derived from the work done on the synchro generator; electricity serves only as the means for transmitting this work from the synchro generator to the synchro motor.

The uses of the synchro generator-motor combination are obvious. If the rotor of the generator is turned manually or automatically to

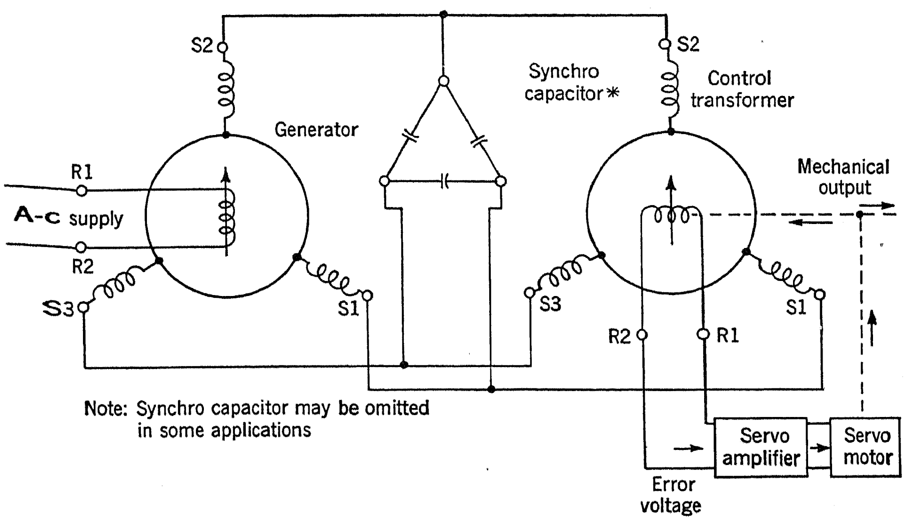


FIG. 10·12.—Synchro generator-control transformer-servo system.

represent the position of a gyrocompass, a water-level float, a valve, etc., then the attached synchro motor, wherever it may be located, will indicate the position of the controlled member. Furthermore, one synchro generator can control several synchro motors so that the desired position can be indicated at a number of different locations.

Synchro Generator and Control Transformer.—A control transformer is used when it is desired to position a load of any sort by a synchro-servo system. Volumes 21 and 25 of the Radiation Laboratory Series cover synchro-servomechanisms in detail. However, a few notes regarding the function and application of this combination of synchros follow.

When connected to a transmitting synchro system as in Fig. 10·12 the rotor of a control transformer furnishes an a-c voltage, the magnitude of which is an indication of the size of the angular error between the control-transformer rotor and transmitting-element rotor, while its polarity or phase is an indication of the direction of the error. This

voltage may be fed to a visual-reading meter and the position of the control-transformer rotor adjusted manually until the meter reads zero, or it may be fed into an amplifier of some sort and used to control a motor that automatically positions the rotor. All automatic controls have antihunt features incorporated in their systems to prevent overtravel and oscillation at coincidence and to improve accuracy and speed of response. The complexity of the actual system depends upon the power and the degree of precision required as well as upon other special control features.

Differential Synchro Systems.—A simple application of a differential synchro is its use as an indicator to show the sum or difference of the angular positions of two synchro generators. In this case, the stator of a differential motor is connected to the stator of one synchro generator

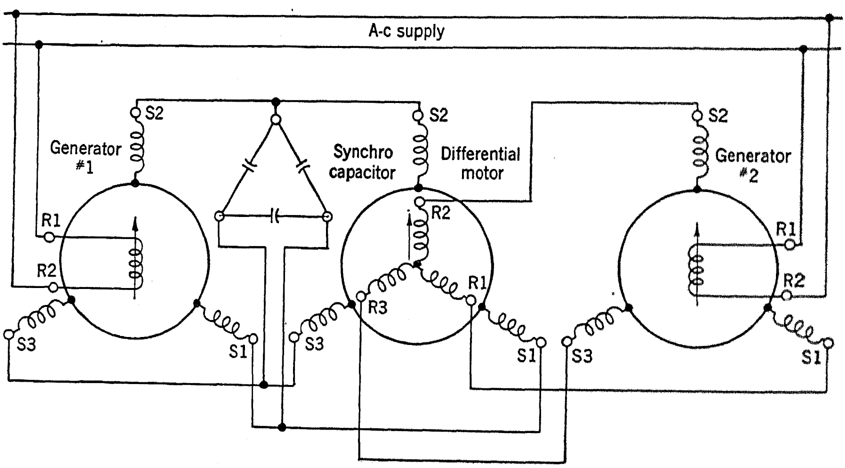


FIG. 10·13.—Differential synchro system.

and its rotor to the stator of another synchro generator as is shown in Fig. 10·13. From the description already given of its operation, it will be apparent that the differential motor will indicate the difference between the positions corresponding to the two electrical signals coming to it. If, however, one pair of its leads—for example, S-1 and S-3—is reversed, then the direction of rotation indicated by the stator winding will be reversed, and the machine will indicate the sum of the positions of the two connected synchro generators. The same holds true for a reversal of one pair of its rotor leads.

When used as a differential generator no damper is required, and the machine serves simply to superimpose upon the synchro-generator output voltages an electrical signal representing the position of the rotor of the differential generator. The resultant signal is then carried on to a synchro motor or to a control transformer, whose indication will obviously be the sum or difference of the positions of the two driven members.

Thus the differential generator is a convenient device for adding corrections either to a synchro indicating system or to a synchro-controlled follow-up mechanism.

Because the differential machine derives its excitation from another synchro, it is usually necessary to use synchro capacitors to assist in furnishing excitation. This machine is designed with the stator winding as the primary, and the capacitors should therefore be connected in shunt across the stator leads.

Two-speed Synchro-transmission Systems.—It frequently happens that the accuracy required from a synchro-transmission system is greater than can be obtained directly from any synchro. In such cases it is possible to gear up the synchro generator so that it turns faster than the driving device, and to gear down in the same ratio from the motor or control transformer. If a gear ratio of 2/1 is chosen, for example, the over-all accuracy of the system is doubled. This method introduces a complication, however, in that the system is no longer completely self-synchronous since it is possible for the motor to "slip a pole" and to find a synchronous position other than the correct one. The danger of such an occurrence increases directly with the ratio chosen; thus, for a 36/1 ratio, there are 35 possible wrong positions for one correct one. To avoid such false indications it is customary to add a duplicate pair of synchros operating at a low ratio, usually 1/1. If the receivers are motors, two dials are used, one for coarse and one for fine readings, similar to the hour and minute hands of a clock. Such a double system is called a "two-speed" system. This use of "speed" in connection with the system as a whole should not be confused with its use to denote the gear ratio; thus a 36-speed synchro is one that turns 36 times for one turn of the actuating device. Common speeds are 1, 2, 10, 18, and 36. If the receivers are control transformers, both are geared with their appropriate ratios to the same servo motor. The error signal is ordinarily taken from the "fine" or high-speed CT, but if the error voltage from the "coarse" CT corresponds to an error of more than about $\pm 3°$ in a 36-speed system, the "coarse" CT takes charge to return the system to approximately the correct setting. The details of such systems are discussed at length in Vols. 21 and 25 of the Series.

In any two-speed system all of the elements of the system must normally be duplicated; thus, in the differential-synchro system of Fig. 10·13, two pairs of synchro generators would be required, and also two differential motors. Normally, with a two-speed system, the only elements that are common to both speeds are the exciter buses, and the servomotor and amplifier if one is used.

10·6. Synchro Capacitors.—Differential generators, differential motors, and control transformers draw magnetizing current from the syn-

chro generators supplying their stators. This current lags behind the voltage by a large angle. Three static capacitors, connected in delta, are usually added to the circuit as shown in Figs. 10·12 and 10·13. The current drawn by the capacitors, being a leading current at almost zero power factor, neutralizes the lagging reactive component of the magnetizing current and thus reduces the total current drawn from the synchro generator by a factor of approximately 4. Three such capacitors, connected in delta and suitably mounted in a hermetically sealed metal container, comprise a synchro capacitor.

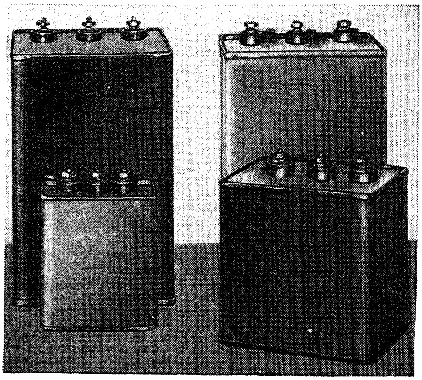


FIG. 10·14a.—Synchro capacitors.

The capacitance of the three legs of the capacitor must be balanced to within 1 per cent in order to ensure proper operation, but the absolute value of the legs may vary over ± 10 per cent.

To obtain maximum benefit from the insertion of the capacitors, it is necessary that the leads from the capacitor to its associated unit be as short as possible. This requirement may involve mounting the capacitor in an exposed position. For protection it is often mounted in a waterproof capacitor box of standard Navy design. A group of standard Navy capacitors and boxes is shown in Fig. 10·14.

10·7. Torque.—Figure 10·15 shows the torque-displacement curve of a Navy 5F synchro motor. This curve is typical of the synchros, regardless of unit size, used by the armed services. It may be seen

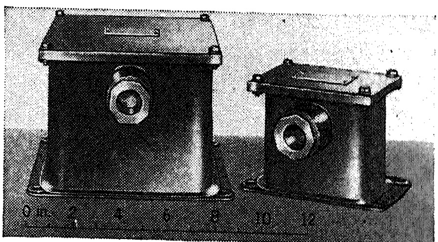


FIG. 10·14b.—Synchro capacitor boxes.

that the rotor excitation current is at its minimum value (0.6 amp) with a 0° displacement and at its maximum (1.8 amp) at 180°. All three stator currents (not shown) are practically zero (20 to 50 ma per stator lead) for a 0° displacement and are maximum for 60°, 120°, and 180° displacements, respectively. Any continuous displacement of over 8° to 10° is likely to cause serious overheating of the rotors.

Torque Gradient.—The torque gradient of a synchro is defined as the slope of the curve shown in Fig. 10·15 expressed in inch-ounces per degree of rotor displacement at the point of zero displacement. Within the normal operating range of the synchro, this curve approximates a straight line with a slope equal to the torque gradient.

Unit-torque Gradient.—The unit-torque gradient of a synchro is its torque gradient when measured against a standard single synchro unit of identical characteristics (i.e., a 1F against a 1F; a 5F against a 5F; etc.).

System-torque Gradient.—The system-torque gradient is defined as the torque gradient of a synchro unit when measured in a system of standard synchro units (i. e., 5G against two 5F's; 5G against four 1F's, etc.).

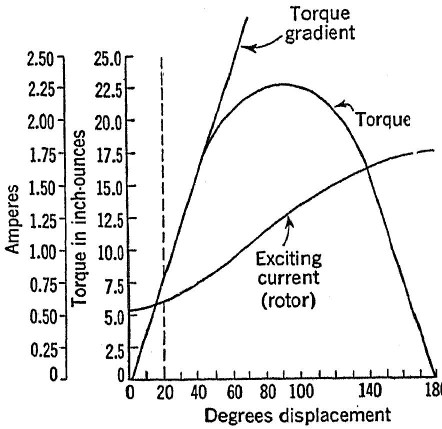


FIG. 10·15.—Typical synchro torque-displacement curve.

Maximum Torque.—Maximum torque is defined as that point on the displacement-torque curve at which a tangent of zero slope can be drawn.

If a synchro motor is driven by a synchro generator whose unit-torque gradient is R times that of the motor, then the actual motor-torque gradient will be $2R/(1 + R)$ times the unit motor-torque gradient—that is, the torque gradient that the motor would have if operated against an identical unit as a generator. If N such motors are operated by the generator of the previous example and the motors are equally loaded, each will develop a torque gradient of $2R/(N + R)$ times its unit-torque gradient.

For example, if a synchro motor whose unit-torque gradient is 0.06 in-oz/degree and a synchro generator with a unit-torque gradient of 0.3 in-oz/degree are used, R is equal to 0.3/0.06 or 5. Then with $N = 1$ the torque gradient of the motor would be $\frac{10}{6}$ times its unit-torque gradient or 0.10 in-oz. With $N = 2$, its torque gradient would be 0.086 in-oz/degree.

Torque-accuracy Relationships.—The basic error figure of a synchro is based upon measurements of errors when a synchro generator of a given size drives a synchro motor of identical size. Because this error is nearly inversely proportional to the torque gradient of the units, it is possible to estimate the errors to be expected from a unit of known torque gradient. An increase in torque gradient gives an approximately proportional decrease in static error.

10·8. Synchro-generator Load Capacities.—The accuracy and available torque of a synchro system are reduced when synchro motors are added. The allowable load depends upon the rated permissible temperature rise of the synchro-generator rotor. This temperature rise depends upon the size of the generator, upon the size and number of motors, and upon their mechanical loads. It also varies with the number of control transformers and differentials connected into the system even though the proper capacitors are used with these units.

No information on load capabilities is available at present for synchro systems using differentials and control transformers as well as motors. To give some idea of synchro-generator capabilities, however, the following table is included. These figures assume no load on the motors other than that of a simple dial. Where greater loading is used, the number of motors should be reduced. Where a differential is listed, it is assumed to be connected to a generator of at least equivalent size.

TABLE 10·4.—SYNCHRO-GENERATOR LOAD CAPACITIES

Generator type	No. 5F units	No. 1F units	No. 5CT units	No. 5CT units with capacitors	No. 1CT units	No. 1CT units with capacitors
1G	none	1	none	1	none	1
5G	4	9	7	14	5	14
5DG	2	5	6	12	4	12
6G	9	18	12	30	11	30
6DG	6	12	10	24	9	24
7G	18	36	24	60	22	60
7DG	12	24	20	48	18	48

10·9. Errors.—All synchro generators, differential generators, and control transformers, even though they are driven units, are subject to electrical errors due to manufacturing irregularities in the windings and in the magnetic structure. Synchro motors have all the errors of synchro generators, and, in addition, have friction errors due to their bearings and brushes.

The electrical errors can (if the windings and magnetic structures are not properly designed) be such as to cause the dial of the synchro motor to lead the reading of the synchro generator at certain sectors about the periphery of the dial. Mechanical errors, on the other hand, being caused by friction in the bearings, always are lagging components of the total error.

Error Plotting.—Figure 10·16 shows a polar plot of the errors of a Navy size-1G synchro generator driving a Navy size-1F synchro motor. The space between the two curves, one showing clockwise readings and the other showing counterclockwise readings, represents the error band

and is mainly due to mechanical errors. Synchro errors may also be plotted in rectangular coordinates. The latter method has the advantage of permitting easier visualization of maximum, minimum, and average errors and error spread, but the symmetry of the errors may be more readily seen from a polar plot.

10·10. Zeroing.—In order for the angular indications at both ends of a synchro system to correspond, it is necessary to orient the machines with respect to each other. There is only one angular position of a synchro rotor for a given set of stator voltages, and, in view of this, a definite relative position has been arbitrarily designated as "electrical zero" for all standard synchro units.

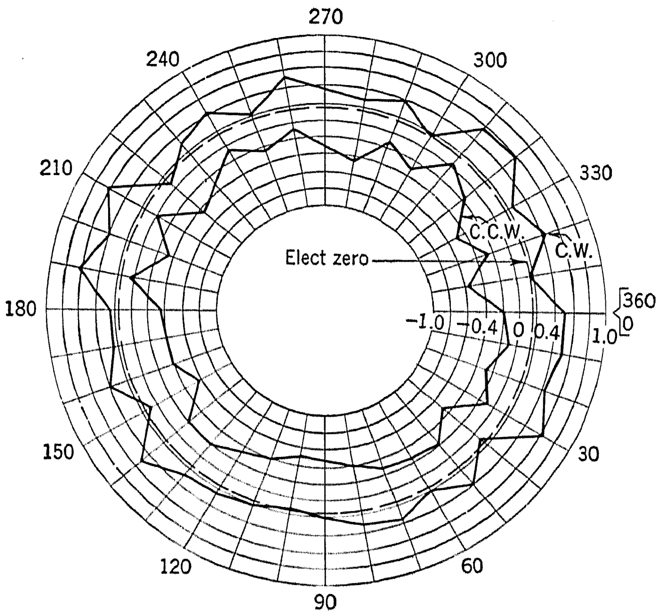


FIG. 10·16.—Static accuracy test. One radial division = 0.2° error.

This zero convention makes it possible to "zero" the dial of a synchro motor on one unit of a system and then to reconnect the unit to a system that has been operating on a "zeroed" basis and have the unit give readings that correspond to its synchro generator without further adjustments. It is to facilitate the zeroing of synchros that they are provided with standarized flanges that are accurately concentric with the shafts. These flanges may be located either on the head end of the frame, as in some aircraft designs, or near the center of the cylindrical frame. They are machined to very close tolerances so that the synchro may be installed accurately in a mounting assembly and held in place by a ring retainer

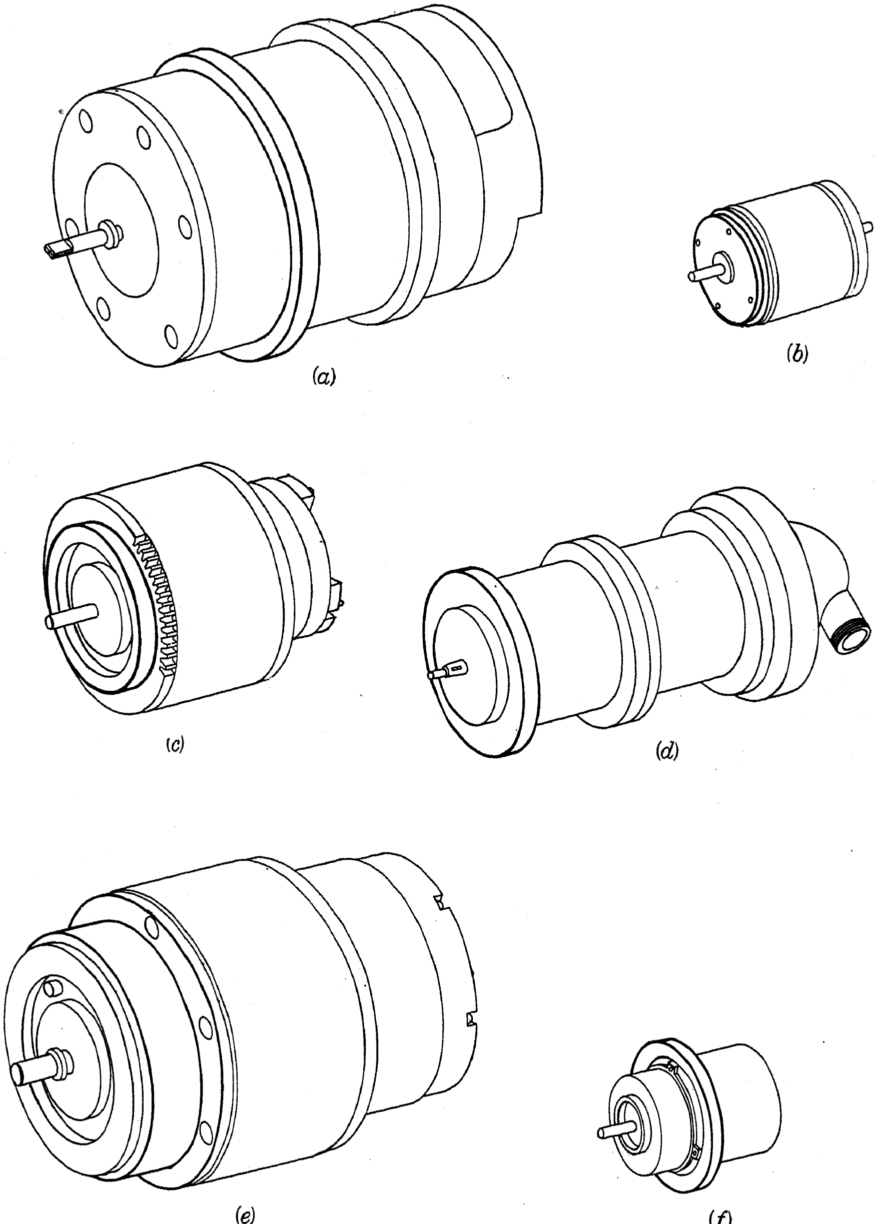


FIG. 10·17.—Typical synchro mountings. (*a*) Navy size 5 synchros, also certain Army styles; (*b*) Bendix-Pioneer AY-100 series; (*c*) Diehl Frame B173185; (*d*) GE size 1 aircraft synchro; (*e*) Army Type VIII, IX, etc.; (*f*) Bendix-Pioneer AY-1 series. (Mounting and locating surfaces outlined in heavy lines.)

or by dogs held against the flange. Thus, by loosening the ring or dogs, the stator may be rotated while energized for zeroing. Figure 10·17 shows six common types of synchro housings, with the mounting and locating surfaces emphasized. The larger synchro generators and motors, when properly connected and energized for the electrical-zero position, possess sufficient torque to position their rotors accurately, but, since control transformers and small differentials require a sensitive low-reading voltmeter or its equivalent for accurate zeroing, it is usually desirable to use a meter for zeroing all units.

The general method used to zero synchros is shown diagrammatically in Fig. 10·18. A synchro may be considered as a rotatable transformer, usually with a ratio of transformation different from unity. For a given distribution of stator voltages, there are two possible positions of the rotor (these positions being 180° apart) depending upon the phase or polarity of the rotor winding with respect to the stator winding. In a synchro generator or motor, when the rotor is near the 0° position, the effective voltages of the stator and rotor windings are in the same direction, and if connections are made as in Fig. 10·18*b*, the lamps will be dim, as the difference voltage will be at a minimum. When the rotor is somewhere near the 180° position, the rotor and stator voltages are opposed as shown in Fig. 10·18*a* and there is a maximum voltage across the lamps.

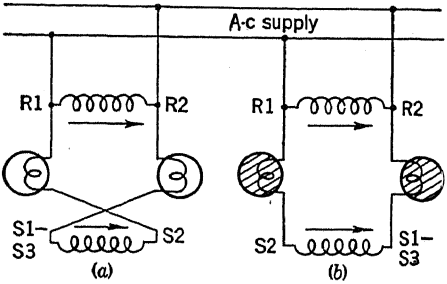


FIG. 10·18.—Fundamentals of zeroing. (*a*) Voltages aiding, lamps bright, windings oppositely poled; (*b*) voltages opposing, lamps dim, windings similarly poled.

In differential units and control transformers, the near-zero position is indicated by maximum voltage across the lamps as represented in Fig. 10·18*a*, and the 180° position by minimum voltage across the lamps as indicated in Fig. 10·18*b*.

For the final accurate positioning of most synchros, a sensitive low-reading a-c–voltage-indicating device is required. This can be a cathode-ray oscilloscope or a vacuum-tube voltmeter in laboratories, and a sensitive low-reading voltmeter or a 2000-ohm headset (telephone receiver) for field applications.

Army-Navy Correlation.—The following set of instructions is based primarily on voltages and designations associated with Navy-type synchros. However, by substituting proper voltages and designations, all information contained herein is equally applicable to all other types of synchros. For zeroing Army synchros, the following voltage and nomenclature changes must be made:

1. Army synchros are designed with a maximum stator-to-stator voltage rating of 105 volts instead of the 90-volt rating of the Navy synchros. This means that wherever 78 volts is indicated in these instructions, it should be raised to 91 volts for Army synchros. Because of the difference in terminology between the Services, the designations R1 and R2 should be interchanged on all single-phase windings and S1 and S3 (or R1 and R3) interchanged on all 3-phase windings.
2. The voltages and designations to be applied to other nonstandard synchros must be derived from their electrical and mechanical constructions.

Synchro Generators and Motors.—To zero a synchro generator or motor whose rotor is free to turn, connect the unit as shown in Fig. 10·19. The rotor will definitely turn to its zero position. Make the necessary mechanical adjustments while the unit is thus energized. In an emergency, 115 volts may be applied directly between S2 and S1-S3, but the unit will overheat and become damaged if left energized more than a very short period of time. (A maximum of 5 min is specified for Navy synchos, 15 min for Army units.)

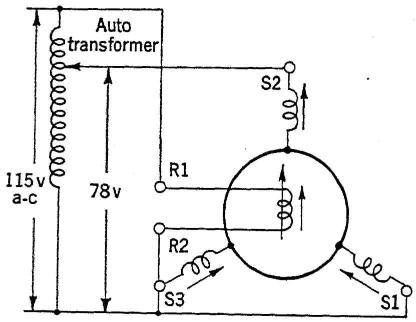


FIG. 10·19.—Zeroing a Navy synchro generator or motor with rotor free to turn. When connected as shown, rotor automatically assumes electrical zero position.

To zero a generator whose rotor is not free to turn, connect the unit and test lamps as indicated in Fig. 10·20*a* and adjust for minimum voltages as indicated by the lamps. This will give the approximate zero position. To refine the zero setting, connect as shown in Fig. 10·20*b* and adjust until the voltage across S1 and S3 is zero as indicated by minimum noise in the 2000-ohm headset or minimum voltage on the sensitive voltmeter. (This voltmeter should be sensitive enough so that a voltage of 0.1 volt may be noticed.)

Differential Generators and Motors.—To zero a differential generator or motor whose rotor is free to turn, connect the unit as shown in Fig. 10·21. The rotor will definitely turn to its zero position, and the mechanical adjustments can be made while the unit is thus energized. As noted before, in an emergency, 115 volts may be applied directly between S2 and S3-S1, and R2 and R3-R1, but the unit will overheat and become damaged if left energized more than a very short time.

The differential units in the small sizes may not develop enough tor-

que to allow zeroing in this manner. In that case, they should be zeroed according to the plan for a unit whose rotor is not free to turn.

To zero a differential generator whose rotor is not free to turn,

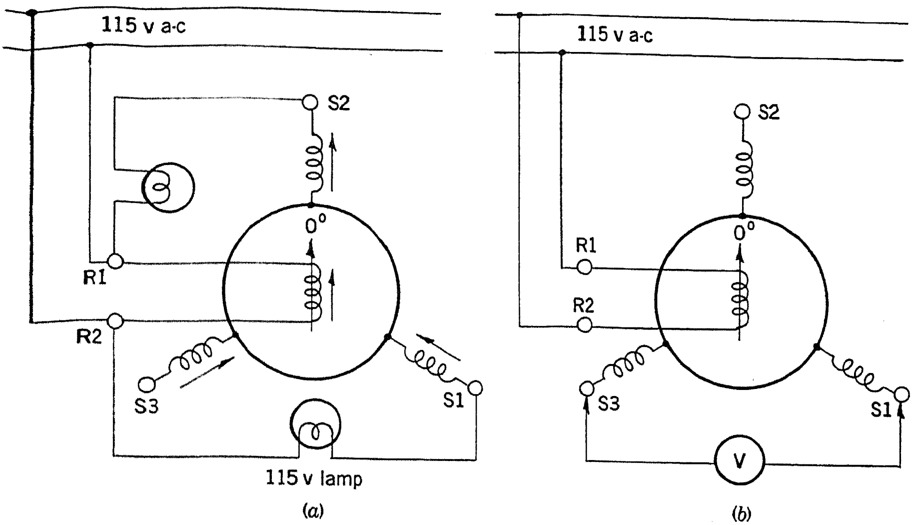


FIG. 10·20.—Zeroing a Navy synchro generator or motor with rotor not free to turn. (a) Adjust rotor or stator for *minimum* brightness. (b) Adjust for zero voltage.

connect the test lamps and unit as shown in Fig. 10·22*a* and adjust the stator or rotor for minimum voltage as indicated by the brilliance of the lamps. This indicates the approximate zero position.

To refine the zero setting, connect as shown in Fig. 10·22*b* and adjust the unit until the voltage across R1 and R3 is zero as indicated by minimum noise in the 2000-ohm headset or minimum voltage on the sensitive voltmeter. It is possible to use 115 volts in place of the designated 78 volts, but for a very short period of time.

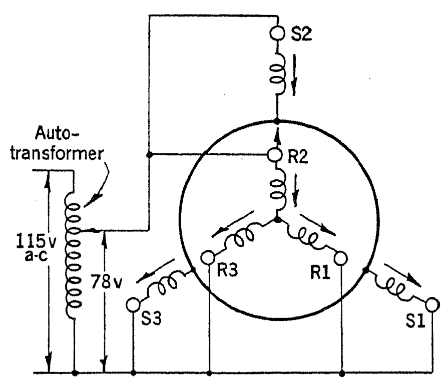


FIG. 10·21.—Zeroing a Navy synchro differential with rotor free to turn. When unit is connected as shown, rotor automatically assumes electrical zero position.

Synchro Control Transformers. To set a synchro control transformer on electrical zero, connect test lamps into the circuit as illustrated in Fig. 10·23*a* and turn the rotor or stator until the test lamps indicate minimum voltage. This is the approximate zero position. Reconnect as shown in Fig. 10·23*b* and refine the adjustment until the

voltage across R1 and R2 is zero as indicated by the headset or the voltmeter.

10·11. Miscellaneous Specifications.—In order to enable an engineer to know the requirements that synchros are designed to meet, the follow-

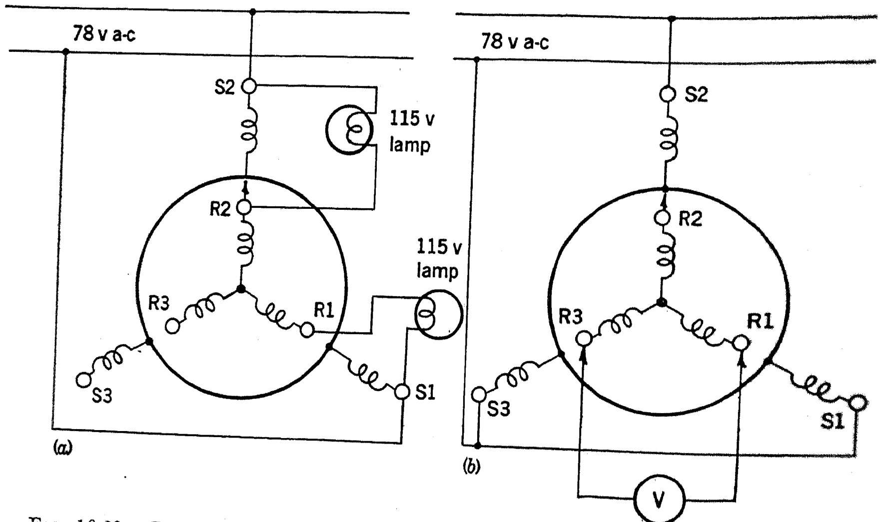


FIG. 10·22.—Zeroing a Navy synchro differential with rotor not free to turn. (a) Adjust rotor or stator for *minimum* brightness. (b) Adjust for zero voltage. The symbol V represents a low-range a-c voltmeter or 2000-ohm headset.

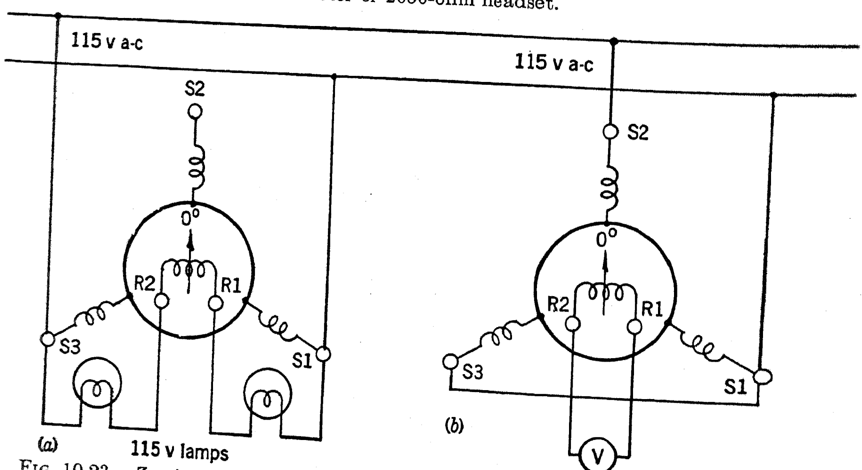


FIG. 10·23.—Zeroing a Navy control transformer. (a) Adjust for *minimum* brightness. (b) Adjust for zero voltage. The symbol V represents a low-range a-c voltmeter or 2000-ohm headset.

ing paragraphs list some of the pertinent requirements for Navy 60-cycle synchros as described in BuOrd Specifications No. OS-671 Revision E. These are the requirements which a manufacturer's sample must satisfy

to become type-approved. It should be emphasized that these specifications pertain only to standard Navy synchros, and that many nonstandard synchros do not meet them.

Frequency and Voltage.—The units shall meet their specified accuracy and performance requirements at their rated voltage ± 10 per cent and at a frequency of 60 cps $\pm$ 10 per cent. The torque gradient increases with increase in voltage and in proportion to the square of the frequency.

Humidity.—The units are expected to stand 95 per cent humidity indefinitely. If they are expected to be exposed to 100 per cent humidity, at which they would be dripping wet, they are provided with weather protection. All studs, springs, washers, nuts, bolts, terminals, and exposed parts shall, where practicable, be protected against corrosion.

Tropicalization.—Synchros are not required to be "tropicalized," but some manufacturers use fungicides such as mercury compounds or pentachlorophenol.

Brushes.—Some companies (Ford Instrument Company and Arma Corporation) use silver brush contacts soldered on to copper brush arms that are backed by thick steel pressure blades; others (General Electric) use phosphor-bronze brushes. The brush pressures for driven units are to be between 10 and 20 g for the 1F synchro-motor, and between 5 and 9 g for the 5F synchro motor. These pressures are to be checked on every unit during inspection.

It has been standard practice to provide silver slip rings on the rotors and silver button contacts on the brushes of these slower-speed Navy synchros. Driving the rotors at higher speed accentuates any tendency to sparking, which, if once started, rapidly burns off the brush contacts.

In order to permit satisfactory operation at the higher speed, brushes are now provided with graphalloy contact material which is composed of 90 per cent silver and 10 per cent graphite. Some manufacturers supply buttons made of this material; others use a rectangular block with a V notch. Synchros treated in this manner are supposed to function satisfactorily at 1200 rpm for 1500 hr continuous rotation.

Shock.—For type approval by the Navy Department the present requirements for shock tests are as follows:

1. Bureau of Ordnance synchros: six blows of 2000 ft-lb—three blows each in two directions; synchro to be energized during this test.
2. Bureau of Ships synchros: one blow of 400 ft-lb, one blow of 1200 ft-lb and one blow of 2000 ft-lb in each of three directions. Total, nine blows.

Vibration.—The vibration requirements for type approval are at present as follows:

1. Frequency—any value between 50 and 1500 cycles per *minute*.
2. Amplitude—not greater than 0.03 in. (0.06-in. total excursion.)
3. Duration—not over 24 hr for all tests.
4. Direction—three directions, one parallel to rotor axis.

Thermal Range.—The units shall be excited with rated voltage and frequency, and the temperature rise of the windings shall not exceed 50°C as measured by the change of resistance method.

The units shall be capable of operating without damage at ambient temperatures from $-25°$ to 55°C.

Lubrication.—Navy synchros were not designed for continuous rotation at speeds higher than 300 rpm. The standard units were, until recently, provided with selected magneto-type ball bearings that were oiled initially at the factory with only a sufficient film of light oil to prevent rusting. In order to permit satisfactory performance at higher speeds, the bearings of all driven units are now being greased with a specified light grease. Any motors driven at high speeds should have greased bearings. However, the application of this grease by the manufacturer would probably prevent the unit from meeting the static-accuracy test requirements of Bureau of Ordnance Specification OS-671.

Endurance.—Driven units shall be given a continuous endurance run of 500 hours at 300 rpm for the standard slow-speed units. High-speed units shall pass a similar test of 1500 hours at 1200 rpm. These tests shall run at normal room temperatures and excitation.

Synchro motors and differential motors shall be driven by a synchro generator following a simple harmonic motion for 500 hr. This motion shall consist of ± 5 complete revolutions (i.e., 10 complete revolutions between reversals) during a period of 7.5 sec for the complete cycle.

Noise.—The unmounted synchro when properly excited shall be free from disturbing noises due to mechanical causes such as knocking in the bearings, loose laminations, etc. The noise or hum emanating from the magnetic structure shall not be considered objectionable.

Shaft End Play.—With the unit horizontally mounted and a force of 3 lb applied to the shaft extension in a horizontal direction, pushing or pulling, the shaft end play shall not exceed 0.008 in.

Phase Rotation.—Phase rotation is the measure of the accuracy with which the rotor of the synchro unit positions itself when the unit is electrically connected for angular positions of 0°, 60°, 120°, 180°, 240°, and 300°. With 115 volts applied to the primary and, in the case of Navy units, 78 volts applied to the secondary, there are six unique positions that the rotor will assume, depending upon the phase relationships of the stator and rotor voltages and the manner in which the voltages are applied to the stator. These positions are illustrated in

Fig. 10·24 which shows the connections necessary for the phase-rotation test.

Time-phase Shift.—The time-phase shift in a synchro system is important since it affects the performance of any attached amplifier

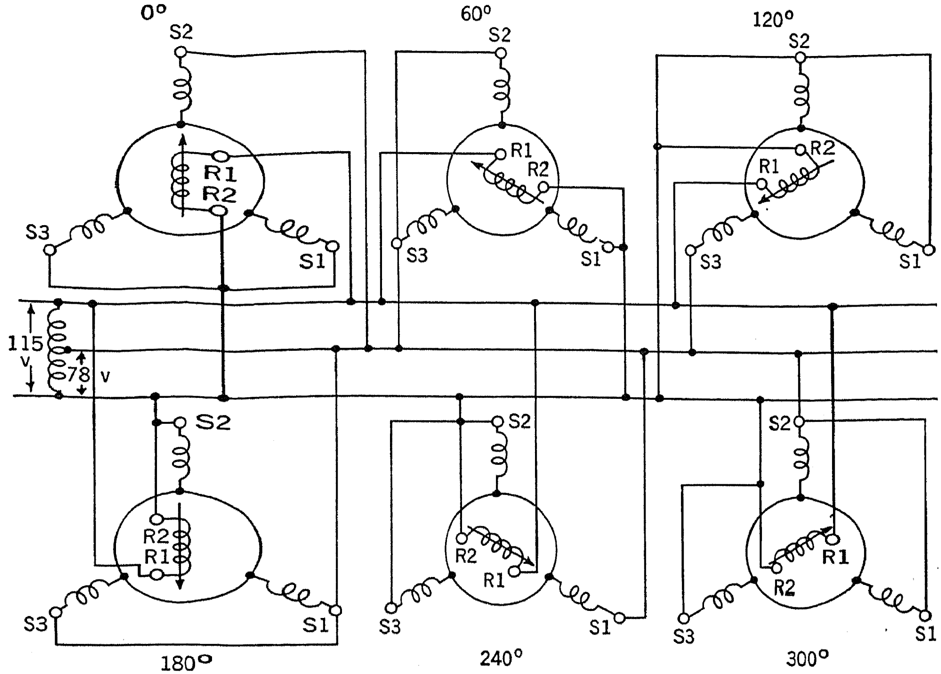


FIG. 10·24.—Phase rotation of Navy synchro generator or motor. Rotor must be free to turn.

and the stability of the whole servo system. Several standard synchro systems have been measured for time-phase shift between various sections. Measurements were made on a cathode-ray oscilloscope and, therefore, are not more accurate than about $\pm 1°$.

TABLE 10·5.—SYNCHRO TIME-PHASE SHIFTS

System No.	Frequency, cps	Generator	Capacitor, μf/leg, delta	Differential generator	Control transformer	Phase shift		
						Gen.	Diff. gen.	C.T.
1	60	5G	none	5DG	1CT	14.5°	18°	30°
2	60	5G	10	5DG	1CT	7.5°	12°	26°
3	60	5G	none	5DG	5CT	14.5°	18.5°	20.5°
4	60	5G	10	5DG	5CT	8°	12°	17°
5	400	2J1F1	none	2J1H1	2J1G1	2.9°	7°	11°

Synchro Matching Transformers.—Because Navy synchros are designed for a maximum voltage between stator leads of 90 volts whereas Army synchros have a 105-volt rating, the two types of synchros may not be interconnected without some sort of matching transformer. Three sizes of these special transformers are shown in Fig. 10·25, but their additional weight and bulk has, in most cases, made them unusable. Consequently, the Army has consented in many cases to use Navy-type synchros in Army equipment.

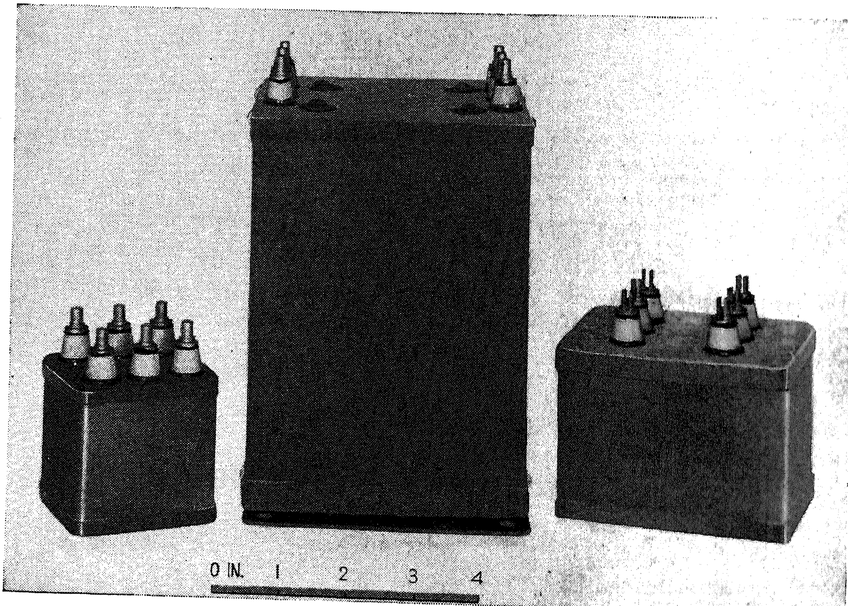


FIG. 10·25.—Synchro matching transformers.

RESOLVERS

10·12. Definition.—An alternative method[1] of analyzing the operation of a synchro system such as that illustrated in Fig. 10·11 is to consider the synchro generator as a vector resolver and the synchro motor as a component combiner or vector adder. In the case of the synchro generator, the vector is defined by the amplitude of the rotor excitation voltage and the relative angle between the stator and rotor. This vector is resolved into components along the axes of the three stator windings. These components are then transmitted electrically to the stator of the synchro motor, where they are recombined to form a vector composed of a magnetic field of a given strength in a given direction. The magnetic field due to the rotor excitation of the motor then aligns itself with this vector field by rotation of the rotor.

[1] See Sec. 10·4 for description of first method.

In the synchro or servo data-transmission systems, both of the above operations are used. Either the resolving or the combining process may, however, be used alone. A synchro, when used in either of these ways, is commonly called a resolver, although this is literally correct only when referring to the former use.

The uses of resolvers may be divided into two major categories: single-frequency systems, and multiple-frequency or nonsinusoidal-waveform systems. The electrical requirements for the different uses vary considerably.

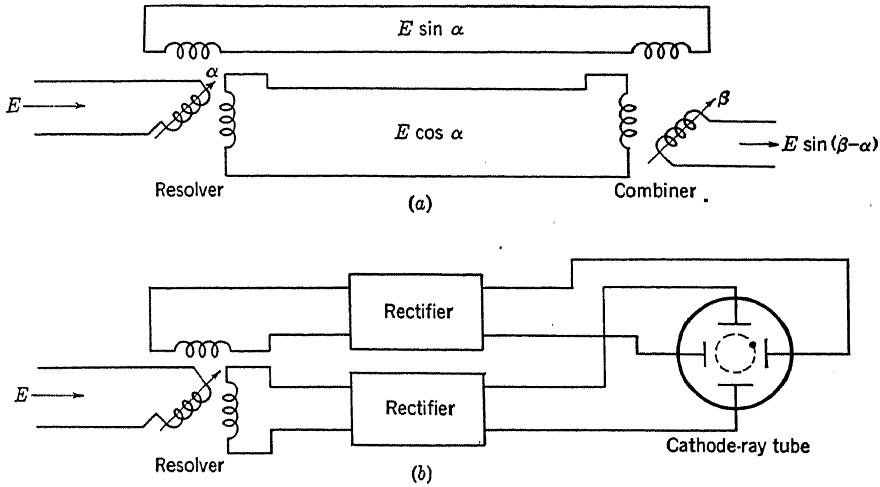


FIG. 10·26.—Use of 2-phase synchro as a resolver.

10·13. Single-frequency Systems. *Resolution.*—When a synchro is used to resolve a vector into components in a single-frequency system, a single-frequency sinusoidal voltage is applied to the single-phase rotor, as shown in Fig. 10·26. The synchro then resolves this vector (excitation amplitude and rotor-stator angle) into components along the axes of the secondary windings. The output voltages may then be used in several different ways. As is shown in Fig. 10·26*a*, they may be recombined in a synchro motor or control transformer for use in a synchro or servo system. (In this case, the secondary windings of the resolver are usually three in number.) However, as is shown in Fig. 10·26*b*, the output voltages may be rectified and used to control the motion of some indicator along the axes of resolution. This indicator may be the beam of a cathode-ray tube or a mechanical pointer. In this application the resolver secondary usually consists of two windings at right angles to each other. When applied to the problem of electronic computation, the secondary can be considered as a coordinate transformer, as it transforms polar coordinates into rectangular coordinates.

Vector Adders.—When used as a vector adder, a resolver may provide either electrical or mechanical outputs or both. These functions are shown in Fig. 10·27. Figures 10·11 and 10·12 show an ordinary synchro motor and a synchro control transformer. In synchro and servo data-transmission systems both act as combiners. In the motor and the transformer, the vector output is in the form of a magnetic field due to the combined magnetomotive forces of the stator windings. In the motor, the rotor turns until the magnetic field due to its excitation is antiparallel to that due to the stator windings. The mechanical output is then the angular position of the rotor with respect to the stator. In the control transformer, the vector output is again the stator magnetic field, but here the rotor winding is maintained at right angles to the

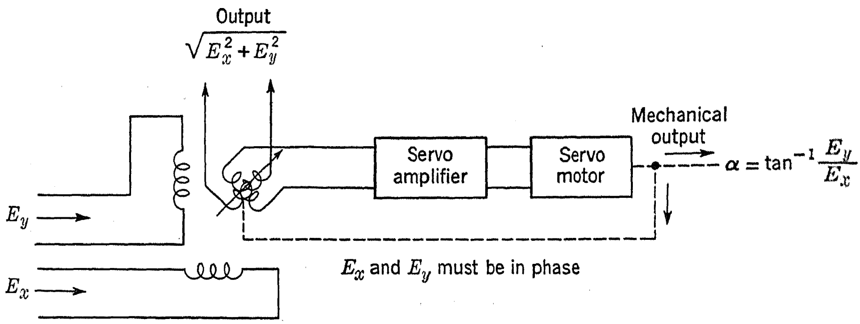


FIG. 10·27.—Single-frequency component-combining circuit using differential resolver.

direction of the magnetic field by the servo amplifier and drive motor. Again the data output is a scalar, the angle between the rotor and stator.

Figure 10·27 shows a resolver as it is often used in computers. One of the rotor windings is attached to a servo amplifier and drive motor and acts as the rotor of a control transformer. This winding is therefore kept at right angles to the vector magnetic field at all times. The second rotor winding is at right angles to the first, and is thus always aligned with the stator field. The induced voltage in this winding is proportional to the amplitude of the magnetic field. Thus a vector output is obtained, the magnitude of which is the magnitude of the signal on the second rotor winding, and the phase of which is given by the angle between the rotor and stator. If the stator windings are two in number and are at right angles to each other, the resolver may be considered as a coordinate transformer, transforming rectangular coordinates into polar coordinates.

Differentials.—Differential generators may be treated as combined resolvers and vector combiners. The action of the 2-phase–to–2-phase differential shown in Fig. 10·27 may be analyzed as follows. Considering only one of the primary stator windings, the signal applied to it is resolved along the two axes of the secondary rotor windings. The signal applied

to the other stator winding is similarly resolved. The outputs of each of these resolutions are induced voltages along the secondary windings. These voltages are additive and produce the total output signals. For computing applications, the process is similar to a rotation of coordinates.

Electrical Characteristics.—Since the units are operated at a single frequency in the foregoing application, the frequency response of the unit is not too important. Most units are designed for either 60-or 400-cps operation. The single frequency also permits fairly accurate temperature and load compensation. In order to maintain the desired accuracy of operation, the synchros must be as lightly loaded as possible. In some cases booster amplifiers may be used to drive low impedances from the resolver outputs. Phase shifts due to the inductive components of the resolver-winding impedances may also be compensated by the simple addition of resistors. Stray capacitances should be kept to a minimum to avoid errors.

10·14. Use of Synchros with Nonsinusoidal Voltages.—Although synchros are normally used with approximately sinusoidal voltages of frequencies varying only slightly from their design frequencies, they can be operated with somewhat decreased accuracy at widely different frequencies if the exciting voltages are properly chosen. Since a synchro generator or resolver is essentially a transformer, its equivalent circuit is the same as that of a transformer, and the same theory applies. Because standard synchros will pass frequencies up to several tens of kilocycles per second without prohibitive distortion, they have been used in various radar-indicator circuits, principally as devices for rotating the sweeps of PPI tubes. An extended treatment of this subject is given in Vol. 22 of the Series, but a brief discussion of the properties desired in a synchro for this application will be given here. Figure 10·28*a* shows the type of sawtooth sweep-voltage waveform that is desired on the tube, and also the type of curve that is actually obtained from the synchro output. The actual curve differs from the ideal curve in three principal respects:

1. The output voltage lags the input voltage by a few microseconds, the lag being practically independent of the length of the sweep. Its effect is a distortion of the PPI map, which is serious for a standard 1G or 5G synchro within about 5 miles of the center and which practically eliminates all signals within 2 miles.
2. The droop at the upper end of the sawtooth waveform compresses the peripheral portions of the map. It is serious only for the longer sweeps.
3. The oscillations after the end of the sawtooth waveform are troublesome only when the duration of the sweep becomes a large fraction of the pulse-repetition period, when they may persist into

the beginning of the succeeding sweep. The cathode-ray tube is ordinarily blanked out between the end of one sweep and the beginning of the next.

Of these three types of distortion the first is usually the most troublesome and the hardest to cure. It is caused primarily by the distributed capacitance and leakage inductance of the windings, neither of which is

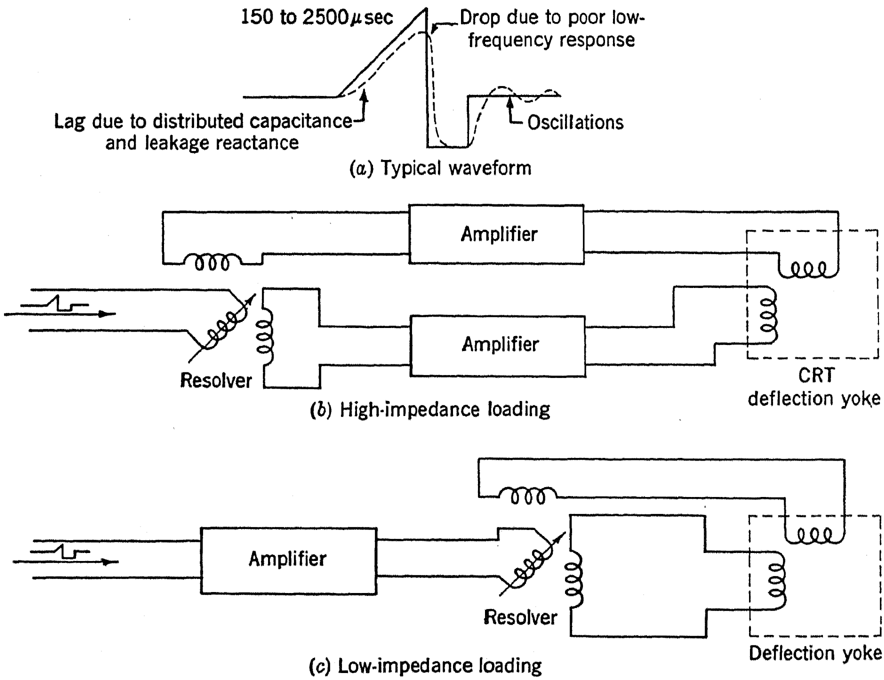


FIG. 10·28.—Use of synchros in CRT sweep circuits.

easy to reduce in a synchro. Some improvement can be gained by using thinner laminations of higher permeability and by reducing the air gap, both of which expedients permit reducing the number of turns for a given inductance, and therefore the distributed capacitance. The decreased air gap also aids in increasing the coupling coefficient, which reduces the leakage inductance. The droop, of course, can be improved by an increase of total inductance, which increases the lag, or by working at a lower impedance level, which is often prohibited by circuit considerations. When necessary, the oscillations can be minimized by suitable circuit design.

Sweep synchros may be used in either of two main types of circuit, and the electrical characteristics required depend upon which of these

types is chosen. In one type, the load on the output windings is of comparatively high impedance, such as the amplifier inputs of Fig. 10·28*b*. In this case the secondary inductance is made as large as possible without sacrificing the high-frequency response, and the primary inductance is kept down for the same reason and to obtain the maximum voltage stepup. The low-frequency response suffers if the primary inductance is reduced too much; therefore an optimum value must be chosen. The flux density in the unit is usually run as high as possible in order to increase the output voltage.

In the second type of circuit, shown in Fig. 10·28*c*, a low-impedance synchro drives a CRT deflection yoke directly. This circuit is used in radar indicators where the accuracy requirements are not great enough to warrant the additional expense of the amplifiers of Fig. 10·28*b*. The yoke is similar in design and construction to the stator of a synchro motor or control transformer, and standard stators can be used to give fair-quality presentations. The cathode-ray beam is deflected by the magnetic field set up by the yoke windings, and the direction of deflection follows the motion of the generator rotor.

For efficient operation into a low-impedance load, the impedances of the yoke and of the synchro output must be matched. In this application the synchro is usually run at a moderate flux density because the required output voltage is low. The response must be maintained to comparatively low frequencies in order to transmit long sawtooth waves.

Because of the requirements for good response at both low and high frequencies, and because the construction of a synchro demands a particular coil construction, most of the improvements in synchros for sweep applications have been in the direction of using improved laminations and in choosing the optimum numbers of turns for primary and secondary. The majority of synchro-driven PPI's that reached the production stage used standard synchros since they were the only ones available, and obtained fairly satisfactory results except for very short or very long sweeps or where close-in resolution was required. Most of the improved synchros tried by the Radiation Laboratory were individual experimental models, and at present very few types are available.

MISCELLANEOUS ROTARY INDUCTORS

10·15. Magnesyns.—Magnesyns are rotary inductors for remote position indication, consisting of a toroidally wound coil and a permanent magnet. They are not power-transmitting units, and therefore, when connected back-to-back, should be used only to drive pointers or similar devices. A single unit may be connected to a synchro through proper matching devices and the combination used as the data-input system for a servomechanism. The Magnesyn is also constructed in a linear form,

but this type has a high inherent friction and should be used only as a generator.

Construction.—The rotary type of Magnesyn consists of a stator and a permanent-magnet rotor. The stator windings are wound on a toroidal form around laminations of a soft, easily saturable material such as per-

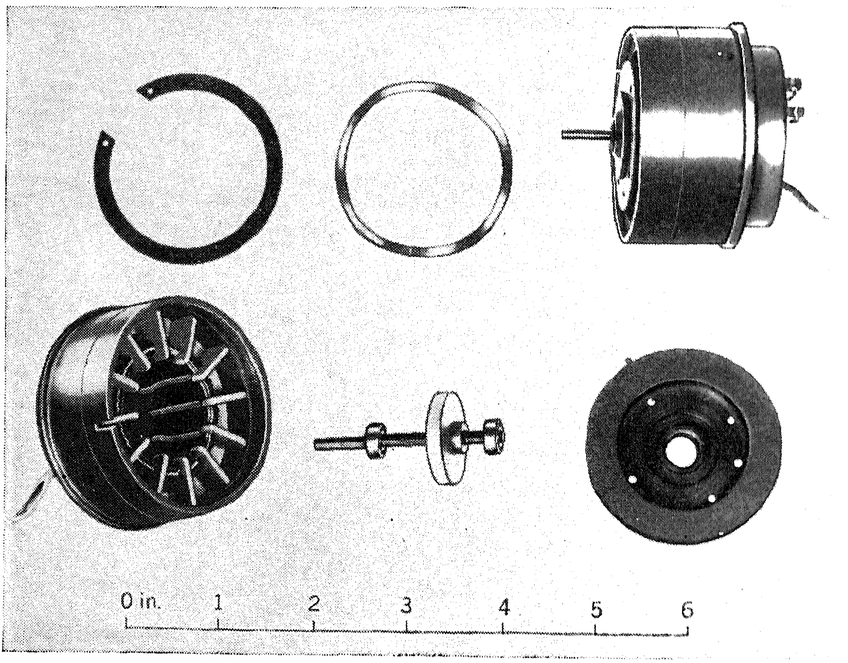


FIG. 10·29.—Mechanical construction of a Magnesyn.

malloy. Surrounding the toroid itself is a cylindrical stack of core laminations which acts to complete the magnetic path when the permalloy has been saturated by a-c excitation. In the center of the toroid is a strong cylindrical permanent magnet, mounted on bearings. The cylindrical shape produces a uniform field around the peripheral toroid. Two taps are taken off at 120° and 240° from the ends of the stator coil, dividing it into three equal segments. The structure is illustrated in Fig. 10·29.

Electrical Characteristics.—Magnesyns are designed for use with 400-cycle 28-volt power, and draw approximately 50 ma for the smaller units and 80 to 100 ma for the larger units.

The units are built to give accuracies of $\frac{1}{4}°$ per unit, thus being capable of $\frac{1}{2}°$ accuracy when used in a back-to-back system. When a linear Magnesyn is used to drive a rotary unit, errors up to 2° may be expected.

Theory of Operation.—In the case of the circuits to be found in a transmitter unit, it can be seen from Fig. 10·30 that the permanent magnet will cause a magnetomotive force to be set up in each half of the annular core, and that the core will be bisected by the axis of the poles of the magnet. This magnetomotive force will be called $H_{d\text{-}c}$. Furthermore, since the core is made of homogenous material, symmetrical in shape and concentric with the magnet, the reluctance of the two magnetic paths will be the same, and $H_{d\text{-}c}$ will be equal in the two halves of the ring.

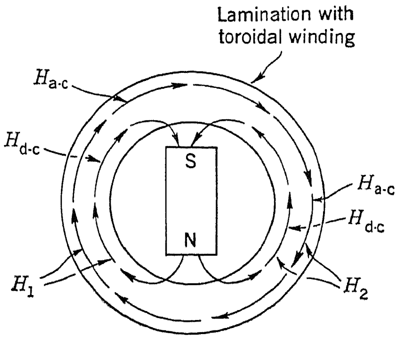


FIG. 10·30.—Magnetomotive forces in Magnesyn core.

The a-c excitation will cause an alternating magnetomotive force to be set up in the core, which will be considered to cause a clockwise flux in the core at a specific time. This magnetomotive force will be indicated by $H_{a\text{-}c}$.

Then the total magnetomotive force in one half of the coil will be

$$H_1 = H_{a\text{-}c} + H_{d\text{-}c}, \tag{1}$$

and in the other half,

$$H_2 = H_{a\text{-}c} - H_{d\text{-}c}. \tag{2}$$

The magnetomotive force gives rise to a flux density B_1, which is made up of two components—namely $B_{a\text{-}c}$, which is common to both halves of the ring and varies at the same frequency as $H_{a\text{-}c}$, and an additional flux density B_x, which exists because of the presence of $H_{d\text{-}c}$ combined with $H_{a\text{-}c}$, or

$$B_1 = B_{a\text{-}c} + B_x. \tag{3}$$

Likewise,

$$B_2 = B_{a\text{-}c} - B_x. \tag{4}$$

From Eqs. (3) and (4),

$$B_{a\text{-}c} = \frac{B_1 + B_2}{2} \tag{5}$$

and

$$B_x = \frac{B_1 - B_2}{2}. \tag{6}$$

If the permanent magnet furnishes a magnetizing field corresponding

to the point H_1 on the low-hysteresis permalloy magnetization curve of Fig. 10·31, the flux and magnetomotive force relationships will be as shown in Fig. 10·32. Curve b is the magnetomotive force due to the a-c excitation. Curves a and c are the total magnetomotive forces in the two halves of the core, as given by Eqs. (1) and (2). Curves d and e show the time variations of the fluxes B_1 and B_2 due to the magnetomotive force shown above. Curves g and f show the time variation of the fluxes $B_{a\text{-}c}$ and B_x, where these two fluxes are defined as in Eqs. (5) and (6). It will be observed that B_x varies at twice the frequency of the fundamental flux $B_{a\text{-}c}$, and is therefore a second-harmonic flux.

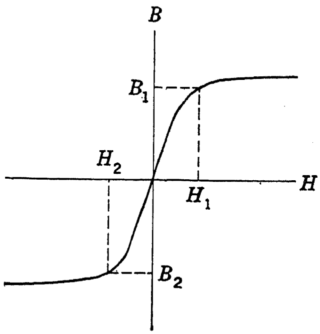


FIG. 10·31.—Magnetization curve of Magnesyn stator.

In the case of the toroidal winding as shown in Fig. 10·33, the exciting voltage E impressed across the coil will be

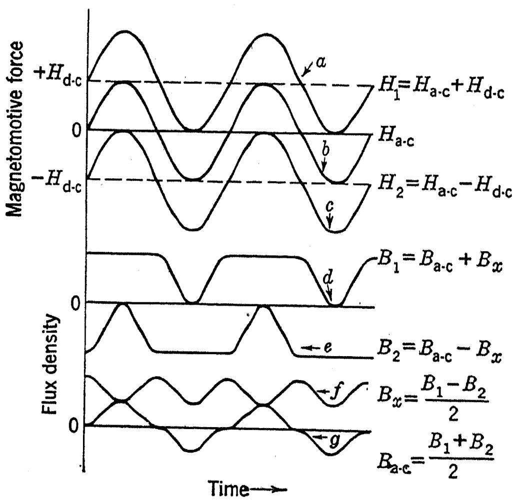


FIG. 10·32.—Magnetomotive force and flux in Magnesyn.

$$E = e_1 + e_2 = e_{a\text{-}c}. \tag{7}$$

Then

$$e_1 = -k\frac{dB_1}{dt} = -k\left(\frac{dB_{a\text{-}c}}{dt} + \frac{dB_x}{dt}\right) = \frac{e_{a\text{-}c}}{2} - e_x,$$

where

$$e_x = -k\frac{dB_x}{dt}.$$

The voltage e_x constitutes a voltage of a frequency double that of the impressed voltage, or a second-harmonic voltage. This voltage is a maximum at the points of the coil adjacent to the poles of the magnet.

If two taps are placed 120° apart as shown and the rms second-harmonic voltages are plotted against angular rotation of the permanent-magnet rotor, the curves shown in Fig. 10·34 will be obtained. Upon comparison with Fig. 10·4 it will be seen that this is identical with the distribution of secondary voltages in a synchro as the rotor is turned.

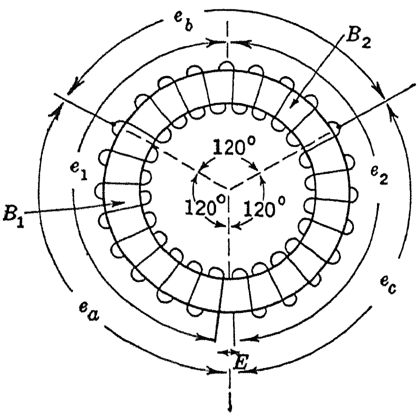


FIG. 10·33.—A-c flux and voltage distribution in Magnesyn.

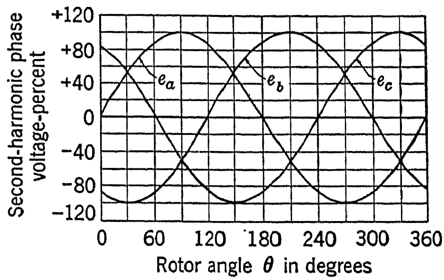


FIG. 10·34.—Second-harmonic phase-voltage distribution in Magnesyn.

There are also fundamental-frequency voltages present, but their amplitudes are independent of the position of the rotor. Therefore, when two units are connected back-to-back as shown in Fig. 10·35, the same

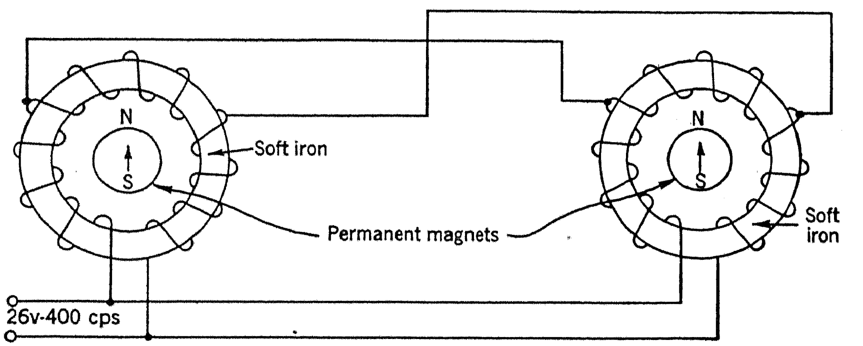


FIG. 10·35.—Rotary Magnesyns in back-to-back circuit.

fundamental-frequency voltages appear at corresponding taps of the two units and are balanced regardless of the position of the rotor; but the second-harmonic voltages change with the rotor position, and any difference in position of the rotors of the two units will produce an unbalance in these voltages for the two units. This voltage unbalance causes cur-

rents to flow which in turn produce restoring torques to bring the rotors into alignment.

Linear Magnesyn.—The operation of the linear Magnesyn is exactly like that of the rotary unit; its construction and its use with a rotary Magnesyn are shown in Fig. 10·36. It consists of a shell-type permalloy magnetic structure with a hollow central leg within which a permanent magnet can be moved longitudinally. The design of the coils and magnetic circuits is such that the fundamental and second-harmonic voltages vary with linear motion of the permanent magnet in exactly the same fashion as in the rotary unit.

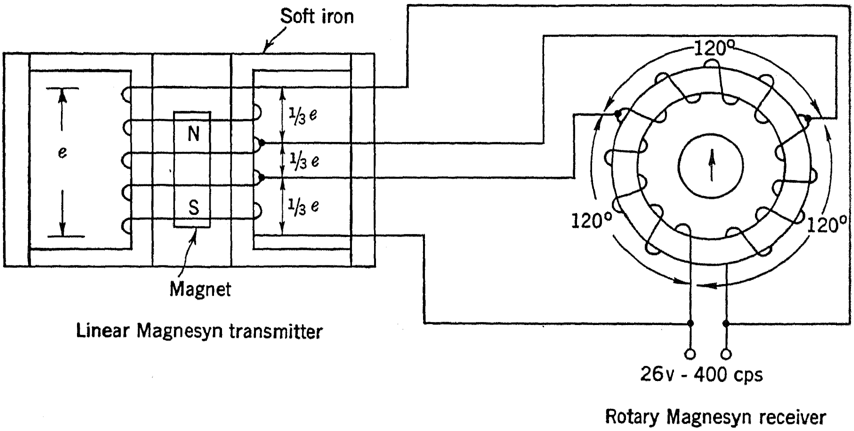


FIG. 10·36.—Linear and rotary Magnesyns back-to-back.

Magnesyn and Autosyn (Synchro).—If it is desired to couple a Magnesyn to an Autosyn a coupling transformer is required to cancel out the fundamental voltages because these voltages must not appear on the Autosyn secondaries. Although the Autosyn was designed for use at 400 cps, it will operate satisfactorily at the second-harmonic frequency of 800 cps. Such a coupling transformer is shown in Fig. 10·37. If the voltage between any two points on the Autosyn stator is determined, only second-harmonic voltages will be found to exist.

For example, the voltage between b and c may be derived as follows:

$$E_{bc} = -\tfrac{1}{6}F + \tfrac{1}{3}F + S - \tfrac{1}{6}F = S,$$

where F = fundamental rms voltage, and S = second-harmonic rms voltage.

10·16. Telegons.—Telegons, like synchros, are used in follow-up systems—that is, a mechanical motion at the transmitter rotor shaft is electrically transmitted to the receiver. This electrical energy is mag-

netically resolved into a torque which displaces the receiver rotor shaft by an equal amount.

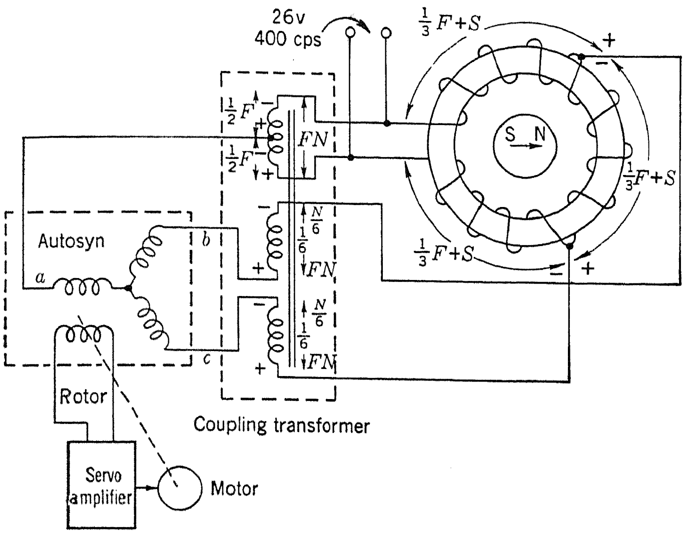


FIG. 10·37.—Magnesyn-Autosyn servo system.

Construction and Theory.—The unit is a single-phase–to–2-phase instrument. All coils are stationary and are wound on a nonmagnetic core. The rotor, which is simply a low-inertia extremely light magnetic vane as shown in Fig. 10·38, is mounted axially on jeweled bearings so that it passes through the single-phase "rotor" exciting winding. Magnetic coupling with the 2-phase "stator" windings exists through the vane. Without the vane, the coupling coefficient from the single-phase to the 2-phase windings is extremely low.

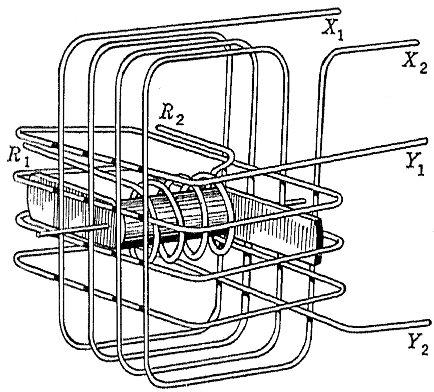


FIG. 10·38.—Telegon construction.

Even with the vane, however, the coupling is still relatively small. The magnetic vane with the two leaves on its ends acts to guide the alternating flux from the "rotor" stationary winding so that it links the two right-angle "stator" windings in a manner which is a function of the angular position of the vane. Voltages are induced in the two right-angle windings according to the relations

$$E_1 = E_{\text{rotor}_{\text{rms}}} \sin \theta$$

and

$$E_2 = E_{\text{rotor}_{\text{rms}}} \cos \theta,$$

where θ is the angular position of the vane with respect to a fixed zero.

These two 90° 400-cps voltages are transmitted to the receiver unit. In the receiver the 90° voltages are combined into an alternating magnetic field that matches the field set up by the rotor excitation of the receiver unit. Schematically, the units can be illustrated as in Fig. 10·39. When the units are matched in rotor angle, no currents flow

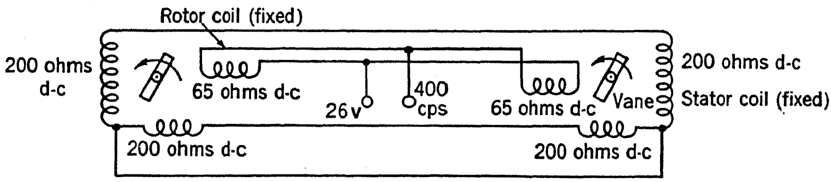


FIG. 10·39.—Telegon system schematic diagram.

between them and hence no torque exists on the receiver vane. If restoring torque is plotted against the angle of the receiver off null, the response curve will be as shown in Fig. 10·40.

The accuracy of the units is ±2° per unit. A back-to-back system, therefore, has an over-all accuracy of ±4°.

Use.—The units were primarily designed to transmit rotary motion to a remote source. However, special consideration has been given to attaching the transmitter rotor to aircraft instruments (altimeter, airspeed meter, etc.) where torque is at a premium. For such applications, it takes only 20 mm-mg to rotate the transmitter rotor. Likewise, it is easily seen that only pointer-indication loads, or the like, can be actuated by the receiver. Although two units back-to-back do not lend themselves to servo control, it is possible to get torque amplification at the receiver by coupling the telegon to a 2-phase–to–single-phase synchro control transformer, and using the a-c error signal from the control transformer to control a servo motor.

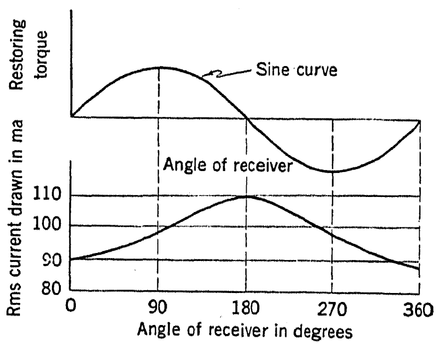
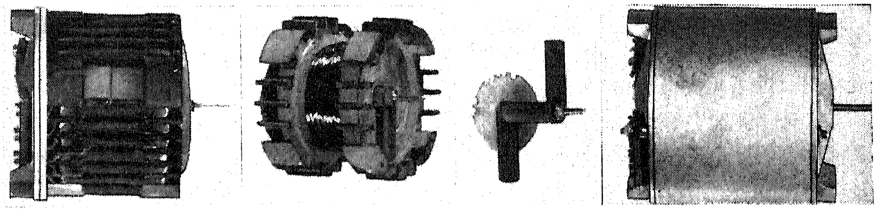


FIG. 10·40.—Telegon performance curves.

Practical application of the Telegon is limited because of its poor accuracy.

Excitation and Electrical Characteristics.—The Telegon requires 90 ma at 26 volts, 400 cps. An indication of the small magnetic coupling can be gained from the fact that a maximum rms voltage of only 6.2 volts is obtained across one of the output phases for a 26-volt input. Figure 10·41 shows an exploded view of a Telegon.



(a) (b) (c) (d)

FIG. 10·41.—Kollsman Telegon and disassembled parts. (a) Unit removed from case; (b) stator windings removed, showing "rotor" winding and vane; (c) vane; (d) assembled Telegon.

10·17. The D-c Selsyn.—All the rotary inductors discussed so far are intended for operation on alternating current. There are some applications where a remote-indicating system is needed that will operate on low-voltage direct current, and several systems have been devised to fill this need. The General Electric Company manufactures such a system in several modifications under the name of d-c Selsyn systems, and inexpensive versions of the same device have been used as fuel-tank gauges in automobiles.

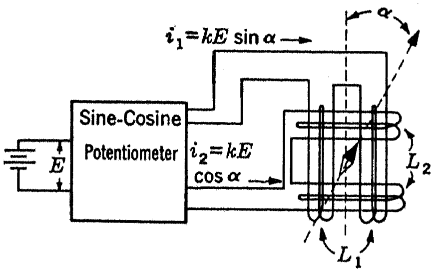


FIG. 10·42.—Principle of d-c Selsyn operation.

The principle of operation can be most easily understood from Fig. 10·42. Here a battery E supplies current to two coils L_1 and L_2 through a sine-cosine potentiometer which operates in such a way that the currents i_1 and i_2 through the two coils are respectively equal to $kE \sin \alpha$ and $kE \cos \alpha$. If the two coils are identical and have their axes at right angles, the resulting steady magnetic field at their common center will be constant in magnitude and its direction will make an angle α with the reference direction. This angle α is the angular position of the potentiometer shaft. Therefore, if a compass needle is placed at the center of the coils it will turn as the shaft is turned, thus serving as an accurate remote indicator of the shaft position. This indication will be independent of the voltage of the battery since a voltage change will affect both coil currents in the same ratio and the direction of the resultant field will be unchanged.

There are a number of variations of this basic system, using either two or three sets of coils and with various added features for particular applications, but the three-coil three-wire system shown in Fig. 10·43 is typical. In this system the transmitter is a potentiometer with a continuous 360° ring winding tapped every 120° and fed with direct current from a battery by two brushes, 180° apart.[1] It can be seen from the construction that if the voltages across the three portions of the winding, *A-B*, *B-C*, and *C-A*, are plotted against shaft angle, a set of curves will result that are roughly like those plotted in Fig. 10·4 for the voltages induced in a synchro-generator stator. If the three leads of a synchromotor stator are connected to the three points *A*, *B*, and *C* of the potentio-

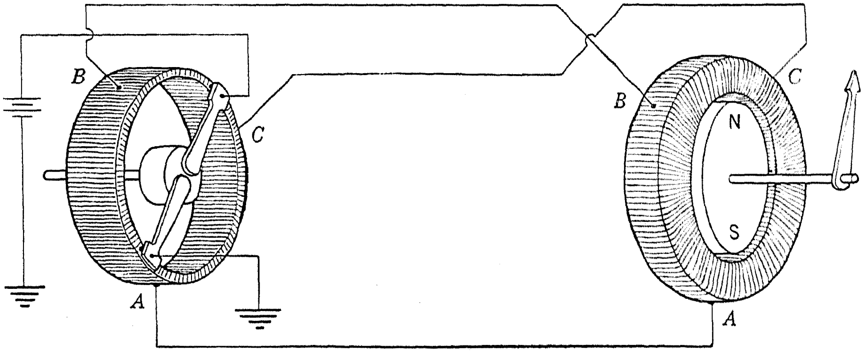


FIG. 10·43.—Three-wire three-coil d-c Selsyn system.

meter winding, a steady magnetic field will result in the stator, and will rotate as the potentiometer shaft turns. The actual indicator used in a d-c Selsyn system may use a Gramme ring, as shown in Fig. 10·43, or it may employ salient poles, with the coils either on the pole necks or on the ring between them, but the end result is the same. The rotor is a cylindrical permanent magnet similar to that of a Magnesyn and similarly mounted, but since alternating current is not present in a d-c Selsyn a stationary copper damping ring or cup is usually mounted in the air gap between the rotor and the pole pieces.

Magnetic-circuit efficiency in a d-c Selsyn indicator can be made fairly high, and the cylindrical permanent-magnet rotor gives an excellent torque-to-weight ratio, permitting the use of plain steel-to-bronze bearings instead of the fragile and expensive jewelled bearings required for some remote-indicating devices. A single system consisting of a potentiometer and one indicator requires about 2 watts at either 12 or 24 volts

[1] One such potentiometer is the Ohmite model DR-125, shown in Fig. 8·31 of Chap. 8.

direct current. Two indicators can be connected to a single transmitter if the dial calibrations are suitably altered. Direct-current Selsyns are light and compact; a complete transmitter unit weighs 0.3 lb and a quadruple indicator, giving four independent indications on a $2\frac{3}{4}$-in. dial, weighs 0.95 lb. Further details on d-c Selsyn systems can be found in the GE catalog, Sec. 6015, pp. 21–34.

CHAPTER 11

INSTRUMENT MOTORS AND TACHOMETERS

BY T. B. MORSE

THE CHOICE OF A MOTOR

The fractional-horsepower motor field, prior to the expansion of the aircraft and radar industries, was rather limited as to the number of types and sizes available. In general, the choice was limited to small universal (a-c–d-c series) motors, induction motors which were seldom available in sizes smaller than $\frac{1}{6}$ hp, and small cheap shaded-pole motors for fans, phonographs, and clocks. They were greatly inferior to those now available after the rapid strides of the last few years.

There have been very few changes in the basic designs of motors, but much work has been done on the utilization of recently available materials in order to obtain the greatest power per pound and per cubic inch, and also on the design of special motors for particular applications. It is because of the large number of special designs that the Radiation Laboratory found it necessary to carry over 300 different types of motors in stock, and these covered only a portion of the small-motor field.

In drawing up a set of specifications for a new motor it is often desirable to include a fairly complete set of data on an existing motor that is as near as possible to the required design. This is particularly important if the new motor is to be ordered from a manufacturer who has had limited experience in making the class of motor desired, since it will give his design department a basis from which to start. For example, manufacturers of industrial motors have often produced aircraft motors three or four times as large and heavy as similar units produced by more experienced companies. On the other hand, if the manufacturer is thoroughly familiar with the design of the particular class of motor involved he will not need such information. In any case, however, it is necessary for best results that the designer be furnished with as complete and accurate a set of performance curves and other specifications as can be obtained, with information as to the relative importance of the various items.

There are several sets of standard motor specifications which have been prepared by various agencies, but they are perhaps less useful than

they might be for various reasons. Some of them are intended for machine-tool manufacturers and other motor users whose requirements are more or less similar, and are not applicable to aircraft or instrument motors. Other specifications have been drawn up by certain classes of users, such as the armed forces, and represent what they would like to have rather than what can actually be manufactured. Military specifications are apt to be general in nature but are so rigid in some respects that very few motors will actually meet them. If the military specifications are quoted to a motor manufacturer it will usually be found that numerous compromises must be made in the design, and these compromises may result in a poorer motor for the application in question than if a new set of specifications had been drawn up on a more realistic basis for the specific purpose in mind.

It is always profitable to draw up a check list of characteristics and desired features when purchasing a piece of equipment, and the following list may serve as a basis from which to construct a more detailed set of specifications of a motor for a particular application. It is necessarily general and lacking in detail but it covers some of the more important points.

- Power source
  - Voltage and voltage regulation
  - Range of voltage variation
  - Ripple (if direct current); harmonic content (if alternating current)
  - Frequency and frequency variation (if alternating current)
  - Effect of heavy starting currents on power source
- Horsepower rating
  - Actual output required (average and peak)
  - Duty cycle
  - Momentary overloads
  - Starting torque; Pull-in torque (if synchronous)
  - Frequency of reversal or starting
- Temperature rise
  - Ambient temperature range
  - Type of enclosure
  - Method of cooling
- Speed
  - Speed regulation
  - Changes of speed with voltage, frequency, etc.
- Control features
  - Control by: inherent motor characteristics
    - integral controlling devices
    - external control systems

Control of: speed
torque
starting current
synchronization, etc.
Noise and vibration
R-f and other electrical noise
Mechanical noise
Vibration and balancing
Frames and enclosures
Frame size
Mountings
Dimensional tolerances
Materials and protective treatments; finishes
Leads and terminals
Brushes and brush mountings
Bearings and lubrication
Maintenance requirements and ease of maintenance
Special features and attachments
Correlation of motor design with design of remainder of equipment with which motor is to be used.

The last point is sometimes the most important of all.

The preceding list does not include a reference to the type of motor. The decision as to the type required is usually based upon the required characteristic, and for most critical applications there is little choice. The two following sections will discuss the more important of the foregoing points, and the remaining sections will describe very briefly the more important types of small motors and also certain kinds of motor attachments and accessories.

11·1. Motor Characteristics. *Power Source.*—The first consideration in choosing a motor is the type of electrical power that will be used to drive it. The voltage, frequency, and normal voltage variation of the source will ordinarily be given, but it is often necessary to specify these and other points with considerable care. If a motor is to be connected to a well-regulated commercial d-c 120- or 240-volt line all that is necessary is to give the line voltage. If the line voltage is subject to wide variation the maximum and minimum voltages must be specified. If this variation is excessive it may be necessary to provide some type of voltage control and to design the motor for the minimum expected voltage. If the speed of the motor must be kept reasonably constant, excessive line-voltage variation may force the use of a centrifugal or other type of speed governor that would not otherwise be required.

In airborne equipment the existence of large percentage line-voltage

variations may be made serious by the comparatively large voltage drop in the motor leads. These leads must be kept small to reduce weight, but the large currents drawn by most aircraft motors (which are usually intended for intermittent high outputs) may result in drops of several volts. For this reason it is often necessary to specify the voltage at the motor terminals, rather than the nominal supply voltage. Many nominal 27-volt motors are actually designed to operate at 26, 25, or even 24 volts. If such motors are operated continuously at full output and 27 volts they may overheat seriously.

A related consideration that will be discussed later is the question of starting current. Excessive starting currents are not usually of sufficient duration to damage the windings of a small motor, but may cause brush or commutator trouble. If the line does not have very good regulation, however, it may be necessary to limit the starting current to protect other equipment on the line. This limitation may be done by auxiliary equipment such as starting rheostats or resistor-relay combinations, but, if possible, it is preferable to accomplish it by suitable design of the motor.

Another rather rarely encountered consideration is the nature of the "direct current" supplied to a d-c motor. The a-c component of most d-c power sources is negligible for motor operation, but if a d-c motor is to be powered from an unfiltered half- or full-wave rectifier the heating due to excessive core losses may be excessive. Such situations arise occasionally in the use of small d-c motors in a-c–powered equipment, and frequently in electronic d-c servo applications.

If the power supply is a-c further complications arise. The only type of motor whose performance is reasonably independent of frequency below 100 cps is the universal series type, and its poor speed regulation and other unfavorable characteristics rule it out for many applications. Aircraft a-c power supplies are notorious for varying in frequency, but frequency variation is a problem in many other fields also. A variation of 20 to 30 per cent in frequency will be tolerated in noncritical applications, so that most 60-cps motors can be operated successfully at 50 cps, but an attempt to operate at 25 cps and rated voltage would probably be disastrous. Operation at a frequency higher than the design frequency will cause less trouble, but ratings must be reduced to make up for the increased iron losses and the operating voltage may have to be increased. Accurate speed regulation of most types of a-c motors on a power supply of widely varying frequency is impossible with normal commercial designs, but there are certain types of motors that will operate at speeds almost independent of frequency over a wide range. One such motor is shown in Fig. 11·17.

Another point that is only of occasional importance is the waveform of an a-c supply. The harmonic content of the usual commercial power

line is small except in rare cases where a line of poor regulation supplies certain types of nonlinear loads such as electroplating rectifiers that, in effect, feed harmonic voltages back into the line. Some voltage regulators, especially the types using saturable reactors as control elements, cause pronounced distortion of their output voltage waveforms. The waveform of many small alternators, particularly the 400-cps aircraft types, is poor. If motors are to be driven from any of these sources of power, attention must be paid to possible trouble from excessive harmonic content. This will not usually affect the characteristics of the motor to any great extent, but in some cases may lead to increased heating and thereby necessitate a reduction in rating.

Mode of Control.—For many applications the inherent characteristics of a standard motor are such that no additional means need be provided for controlling speed, etc. In others the requirements are so stringent that elaborate control systems are required; such systems are discussed in Vols. 21 and 25 of this series and will not be elaborated here. For the intermediate class of applications, however, there are several simple control methods, and for best results it is necessary to consider the control and the motor as a unit rather than to pick a motor and hang a control on it. Many motor manufacturers are now supplying various types of motors with centrifugal speed governors attached and with the characteristics of motor and governor matched to secure the most desirable characteristics. When such controls are required the manufacturer should be informed as fully as possible of all the conditions of operation and of the required characteristics so that the control will be given a chance to work properly. This applies not only to centrifugal speed governors but to all types of control, and is the more important the more critical the application.

Speed control is only one of the types of control which it may be necessary to consider. Another important type is the limitation of starting current. This must be considered for large or heavily loaded motors, or in cases where momentary voltage dips cannot be permitted on the line that feeds the motor, and particularly for motors in reversing service such as some antenna-scanning drives. In such cases it is sometimes possible to use a motor that has an inherently limited starting current, and if it is possible, this should be done. If it is not possible some other means must be used, such as series resistors that are automatically cut out by relays after the motor has come up to speed. Other types of control such as torque limitation or synchronization of the position of two or more motors may be needed in certain cases and may require modification of the motor design.

Noise and Vibration.—Consideration must often be given to vibration or to mechanical or electrical noise generated by a motor. Vibration

may effect components that are mounted on the same chassis or structure as a motor. The motor may be isolated to some extent by shock-mounting the motor frame and providing a flexible vibration-absorbing coupling in the output shaft, but it is usually easier and far better to use a motor with a properly dynamically balanced rotor. Bearing and brush noises, slot whine, and winding hum are occasionally annoying if the motor is to be used in a quiet environment. Certain types of starting switches make an annoying pop in operation and have proved to have a strong negative sales appeal in domestic appliances. The quieting of airborne noise is not particularly difficult for most types of motors unless the permissible noise level is very low; for such applications as sound-motion-picture camera drives the best solution is usually to enclose the whole equipment in a sound-insulated booth or "blimp."

The elimination of electrical noise is a far more common problem, and may be extremely difficult. Except for pops due to starting switches and chatter due to vibrating-contact governors, nearly all motor noise is due to sparking commutators. Slip-ring brushes are usually quiet if the ring and brushes are in good condition. If a motor with a sparking commutator is used on the same electrical system with low-level electronic equipment some kind of filtering or isolation will almost always be necessary. This filtering may be done in the power leads of the low-level equipment, but is much easier and more effective if done at the noise-generating equipment itself. One of the simplest and best methods is the connection of small paper condensers from each brush-holder to the grounded motor frame. It also helps if the motor is connected with one brush grounded, leaving the series fields on the "hot" side of the line to act as a choke. In many cases there will be sufficient space to permit mounting the condensers inside the end bell; if this is impossible they should be mounted as closely as possible to the brush leads and covered with a grounded metal shield. Additional precautions include the provision of a motor-frame ground connection of the lowest possible impedance and sometimes include the covering of all openings in the motor frame over $\frac{1}{8}$ in. diameter with grounded metallic screening. If the brush holders have the usual insulating caps they may have to be covered in turn with grounded metallic covers.

Horsepower Rating and Temperature Rise.—The term "motor rating" is ambiguous unless all of the operating conditions are specified. For example, the term "continuous duty" may be chosen. For commercial motors it is usually specified that the ambient temperature may not exceed 40°C. In many radio and radar applications it is found that the ambient temperature may be as high as 90°C, and for a continuous-duty rated motor the rating must be greatly reduced or an entirely new design may be required. "Intermittent duty" is also a rather tricky

rating. For example, a motor may be rated for a 2-min, a 5-min, a 10-min, or a 20-min duty under specified conditions of ambient temperature and intervening cooling periods. These periods may be from 2 to 10 times the operating period. For example, the same size motor with the same windings may be rated either for $\frac{1}{10}$ hp intermittent duty on a 5-min cycle or for $\frac{1}{20}$ hp continuous duty, at 50° ambient temperature. If this temperature is raised to 60° or 70°C, the rating may be reduced to $\frac{1}{30}$ hp continuous, or the motor may not be suitable for the application in question. A good example is the General Electric Company aircraft motor in the Size 25 frame. It may be rated for as much as $\frac{1}{4}$ hp for 1 min at 7500 rpm, while the maximum continuous rating for the same frame and speed is not over $\frac{1}{100}$ hp.

Another factor that enters into the rating of a motor is the frequency of starting and stopping, or the frequency of reversal. Unless special precautions are taken to limit the starting or reversing currents in the larger motors, serious overheating may result. Small motors of 30-sec, 1-min, or even longer intermittent-duty ratings ordinarily do not have internal fans, since the operating time is so short that heat conduction to the exterior of the windings where the fans would do some good is inadequate. On a continuous-duty motor, however, proper air ducts must be provided to give the cooling air access to the hot spots.

The cooling problem has been met in different ways by different manufacturers. For the small permanent-magnet motors such as the Diehl or Delco units a flat mounting surface is provided, it being intended that the motor be mounted on a heavy body of metal so that heat can be conducted away. On larger motors, integral fans are provided and in some cases special ducts are cast into the motor shell and the cooling air is blown through these. In others a shroud is provided over the motor, the fan is mounted externally, and the air is directed along the outer surface of the motor shell. On some Diehl units a fan is provided in the same housing which is operated by a separate motor that runs all the time, independently of the main motor. This method is especially valuable for servo motors and others that run at reduced speed for much of the time.

The exterior finish may make a considerable difference in the operating temperature of a motor. If there is no provision for cooling other than radiation cooling, a motor with a brightly polished or nickel-plated shell may run as much as 10° hotter than one with a dull black finish.

In certain hazardous locations, as on gasoline pumps, totally enclosed explosion-proof motors are necessary. Such an enclosure usually reduces the rating of a motor by about 50 per cent, but the intermittent nature of most such applications frequently permits a reasonably small motor to be used.

The method of cooling a motor should usually be left to the manufacturer's design department. It is best to specify the operating conditions as completely as possible, let the manufacturer supply the type of motor he feels most suitable, and then make tests to determine how well the specifications have been met.

The ambient temperature range should be specified on a realistic basis. The usual military specification of $-55°$ to $+70°C$ is difficult to meet, particularly with respect to lubrication, and it is usually necessary for the designer to favor either the upper or the lower portion of the range. If it is not actually necessary for the motor to work over such an extreme range the limits should be moved inward to correspond with the facts.

Motor Speeds.—Motor speeds have not been standardized for small units other than the 60-cps induction motors, each manufacturer designing motors for particular applications. The General Electric Company commonly supplies aircraft motors with speeds of 1750, 2800, 3800, 5800, and 7500 rpm. Many of the smaller manufacturers try to adhere to these ratings, although 3600 and 6000 rpm are also fairly common. The ratings of 60-cps a-c motors are usually either 1725 or 3450 rpm, although a few 1100-rpm motors are available. The ratings of 400-cps motors (in which the 2-pole synchronous speed is 24,000 rpm) are usually 12,000-, 8000-, or 6000-rpm, the 8000-rpm being the most common. In the smaller sizes considerable difficulty is encountered in finding sufficient space to wind the required number of poles for the lower speeds.

The speed characteristic required for a particular application will often determine the choice of motor type, especially for d-c motors. In general the speed regulation is poorest for series motors, much better for shunt-wound motors, and still better for compound-wound motors. Very good speed regulation is obtainable from the use of integrally mounted centrifugal speed regulators. In cases requiring two-speed operation a double-commutator d-c machine may be used, such as the John Oster unit shown in Fig. 11·2. Multispeed operation can also be obtained in certain types of pole-changing a-c motors, although here the choice of types and sizes is limited.

11·2. Miscellaneous Features.—Beside the strictly electrical and mechanical features of a motor there are a number of others that should not be overlooked in choosing an existing motor or in drawing up a specification for a new one.

Frames and Enclosures.—Most motors of the fractional-horsepower class or larger can be obtained in several types of frames or housings. Of these the most common are the conventional open frame and the drip-proof, the splash-proof, the totally enclosed fan-cooled, and the explosion-proof housings, in increasing order of degree of enclosure, complexity, weight, and expense. Motors may also be purchased less frames, or less

certain parts of the frame, for incorporation into machine tools or other equipment in which suitable provisions are made for mounting the rotor, stator, and accessories. The variety of housings is less for motors smaller than about $\frac{1}{4}$ hp, and the most instrument motors are furnished with only one type of housing. Many types of instrument motors, however, are totally enclosed, which renders them less liable to trouble from dirt and corrosion than the conventional open-frame type.

The mounting dimensions and styles of fractional-horsepower and larger motors have been more or less standardized in the interests of interchangeability. Standardization has also been carried out for certain special classes of motors, particularly for aircraft motors, and standardized mountings should be used wherever possible. There are many cases, however, where special mountings are necessary, and if a particular motor is of such a special nature that it cannot be replaced by some type of standard motor a standard mounting should not be allowed to force an unfavorable compromise in some more important design feature.

Most motors in the past have been mounted by mounting feet or flanges in a plane roughly tangent to the cylindrical motor shell. In the interests of compactness, easy alignment, and less weight, however, aircraft motors are usually end-mounted, and many instrument motors are mounted in the same way.

Concentricity and dimensional tolerances on mounting and locating surfaces should be given to the required accuracy, but no more. A motor that drives a fan or pulley mounted on its shaft need not be accurately located, but if it is geared to its load the required accuracy is determined by the design of the gear box. If tolerances tighter than normal production tolerances are specified the manufacturer must use selective assembly or must make certain parts with greater than normal accuracy, usually in his tool room or model shop, and in either case delivery will be retarded and production cost will be considerably increased.

Shaft end play may be of importance in some applications. The design of the equipment associated with the motor should be such as to permit a reasonable amount of end play, say 0.010 in., if possible; if not, the shaft should be located longitudinally by one bearing and the other bearing should usually be backed with a loading spring. If the locating bearing is the one closer to the output end of the shaft the effects of differential expansion of shaft and housing will be minimized.

Materials and Protective Treatments.—It is usually best to allow the manufacturer to decide what materials are to be used in the construction of the motor, and what the internal construction is to be. The less the interference with his standard production techniques and the fewer the special parts required the less expensive and often the more satisfactory the final product will be. In many cases, however, it is necessary to

specify certain materials or details. For example, Navy specifications forbid the use of cast iron for motor frames because its brittleness renders it vulnerable to damage from shock. If the piece of equipment of which the motor is a part is itself shock-mounted, however, this objection loses much of its force and it would be in order to apply for a waiver of this restriction. Standard motors are usually adequately protected against the degree of atmospheric humidity prevalent in the temperate zone, but a motor intended for tropical service should be tropicalized. This treatment should include not only impregnation with a fungicidal lacquer, but also the provision of special materials for motor and coil-lead insulation, slot insulation, slot wedges, etc. Standard maple slot wedges, for example, are excellent culture media for fungi, often even when coated with a fungicidal lacquer, and should be replaced with more suitable materials. Mild-steel shafts should be replaced by stainless-steel shafts, and all parts that are subject to corrosion in humid conditions should be adequately protected. Motors furnished as spare parts for other equipment should be packed in sealed cans with a drying agent.

Leads and Terminals.—The number, type, and location of motor leads and terminals should be specified. For many purposes the standard AN connectors are suitable, as they can be obtained in a wide variety of types and sizes to fit all ordinary requirements. In some cases the motor will be installed in an inacessible position or will be so closely surrounded by other equipment that it will be impossible to use a connector. In such cases it will be necessary to use wire leads, and the position of emergence from the housing, the length, size, and color or other coding of these leads, should be carefully specified.

Brushes and Brush Mountings.—Much developmental work has been done on motor brushes. In the early days of military aviation it was found that ordinary carbon brushes which might have lives of several thousand hours at sea level were ground to destruction in 10 to 15 min when operated at high altitudes. This was later found to be due to the dissociation, under conditions of low oxygen pressure, of a film of copper oxide that forms on the surface of the commutator at normal pressures and that acts as an effective lubricant. Satisfactory brushes were eventually produced by impregnation with certain organic materials or with halogen compounds such as lead iodide. Many manufacturers are now producing such brushes, each with his own particular process of impregnation. Sometimes this is done before pressing and baking the brush, sometimes by dipping the completed brush.

Of the many types produced, "altitude-treated" brushes are available that are suitable for operation at both low and high altitudes. It is preferable not to specify such brushes if high-altitude work is not necessary, since in many cases the treating compound has a tendency to

bleed out and gum up the commutator. This is especially true of the very small motors and generators used as instrument and computer drives, tachometers, etc. The manufacturers, therefore, indicate the type of brush to be used in a particular unit. Details of the impregnating compounds and treatments used are beyond the scope of this volume.

Another method of varying the properties of a brush material is the combination of such metals as silver or copper with the carbon, either in the mix or by treatment after pressing. High-metal-content brushes are satisfactory for slip-ring use and for generators and tachometers where voltage drop across the brush must be held to a minimum and currents are not large. All-metal brush materials such as copper gauze are used for low voltage drop and very heavy currents, as on starter motors and plating generators, but are not recommended for general use. Copper-carbon brushes with a high metal content (up to 80 per cent) are used for the same purpose. One trouble with both these types is that the low-resistance particles collect in the cracks between commutator segments and tend to short-circuit them. For this reason the mica spacers on such commutators are not usually undercut, even though this tends to increase the liability of sparking. Another difficulty in the use of all-metal brushes lies in the fact that when similar metals are rubbed together, as copper on copper, they have a tendency to seize and gall. This causes serious difficulties, especially in the case of silver brushes on silver slip rings. If dissimilar metals are used, as silver on stainless steel, the tribo-electric effect produces appreciable electromotive forces between the metals, which may lead to difficulties except when the armature voltage is comparatively high.

One difficulty often encountered with motor-generator sets and dynamotors is that heavy starting currents cause intense local heating and expansion of the contact surface, with consequent cracking and disintegration of the brushes. In general, metal-graphite brushes are suitable for 6- to 28-volt applications, but not for high-voltage armatures or for those applications in which there is a high voltage between commutator bars.

Another consideration that is important with any brush that may have to carry appreciable currents is the provision of a "pigtail" connection from the brush to the lead or holder so that the current will not have to flow through the brush springs. Spring materials have comparatively high resistivities, and a brush spring will be annealed and ruined in a moment by excessive current such as might be caused by an accidental short circuit. Most motor brushes are now provided with a pigtail of extra-flexible stranded copper wire that is imbedded in the brush material at one end and carries an eye or contact lug at the other. Certain types of brush holders in which the brush pressure is produced

by a spring that is not electrically connected to the brush do not require the pigtail for the protection of the spring, but it is still useful to reduce brush-circuit resistance. Brushes that slide radially in a round or rectangular tube, as in most small d-c motors, do not make good connection to the tube, especially after they become soaked with oil or grease from the bearings. In very small motors where the provision of a pigtail would be difficult or impossible and where current must be carried by the brush spring beryllium copper may be used, since it retains its springy qualities up to fairly high temperatures.

The actual design of the brush holder is frequently a matter of importance. The common tubular holder is satisfactory for most purposes if a pigtailed brush is used, but it should be constructed either with both holder and brush cap flush with the motor shell or with an integral shoulder to prevent the holder from being driven inward against the commutator by an accidental blow. Such an accident will necessitate a major overhaul of the motor, including turning down the damaged commutator. Another precaution in this type of brush holder is the provision of insulating brush caps so designed that no metal that is electrically connected to any part of the motor circuit is accessible from outside the motor. There is no excuse for the "hot" exposed metal brush caps frequently found on cheap motors, and their presence on motors used in home appliances is criminal.

In certain applications, particularly in Amplidyne generators and precision d-c tachometers, it is essential to use a brush mounting that will not permit the brush to move tangentially with respect to the motor frame. In the case of some aircraft Amplidynes the brushes are in the form of a segment of a cylinder and are mounted on an arm that swings about an axis in the center of curvature of the brush and parallel to the generator shaft. A somewhat simpler construction which does not require curved brushes is illustrated in Figs. 11·3*d* and 11·7. In the examples shown, the brushes are rigidly attached to triangular brush arms that pivot about axes that are at right angles to the shaft axis and are located near the outside surface of the generator housing. The finger-brush construction of the Elinco generator of Fig. 11·4 is also effective in eliminating sudden brush shifts, but a gradual change of effective brush position may take place because of wear.

Bearings and Lubrication.—One of the most prolific causes of failure of small motors has always been the bearings. The choice is limited to ball bearings and sleeve bearings, the Army and Navy generally favoring the former exclusively. Powdered-metal sleeve bearings, however, have many desirable features. They are especially suited to applications at normal or high ambient temperatures, but have a tendency to seize at very low temperatures. In fan and blower duty, however, this is not a

serious defect because cooling is not necessary at the lower temperatures. By the time the temperature has risen sufficiently to require that the cooling system start working the bearings will have warmed up sufficiently to operate. Sleeve bearings are almost essential for very-high-speed operation (above 10,000 rpm), since at such speeds rather elaborate precautions are necessary to ensure proper lubrication of ball bearings. At high speeds these require very little oil, but must have an unfailing supply. Grease is impractical for high-speed operation since the particles of grease do not have time to get out of the way of the balls as they roll on the races. The result is that the balls slide rather than roll with consequent overheating, galling, and destruction of the bearing in a very few seconds.

Sleeve bearings require much care in their application. The bearing surfaces should be broached or bored but not reamed, since the burnishing action of a reamer has a tendency to close the pores in the surface of the metal. After sizing it is necessary to cut the lip off the oil grooves to eliminate its tendency to shave the film of oil from the journal, causing rapid wear. If sleeve bearings are fitted loosely enough for low-temperature starting they are frequently too loose for normal-or high-temperature operation. Under very low-temperature conditions ball bearings may be preferable, though they still have drawbacks.

Sleeve bearings are satisfactory for long life and quiet operation if a suitable felt- or wool-packed oil reservoir is provided. They are particularly applicable in dirty or dusty locations, since they are much less liable to damage from grit than ball bearings. It is desirable, however, to provide some means for periodic lubrication of sleeve bearings, even if this requires running a length of tubing from the oil reservoir to some accessible outside point. Sleeve bearings are also preferable to ball bearings when the equipment is infrequently used or is subject to long periods of storage, since they provide a constant and large-area film of lubrication. Under these conditions ball bearings are subject to corrosion and to deterioration of the lubricant. The grease may turn rancid or its oil and soap components may separate, destroying its lubricating properties and gumming the bearing with hard sticky soap. Ball bearings that have been in storage over six to nine months should be returned to the manufacturer for cleaning and relubrication. This is not a field job.

Properly fitted sleeve bearings can have a coefficient of friction comparable to that of the average ball bearing, but when extremely low friction is necessary ball bearings must be used. The original open type of bearing was susceptible to the picking-up of dirt, dust, and fuzz, and to the loss of lubrication due to seepage and leakage, especially at the higher temperatures. For example, ball bearings operated with the

shaft vertical are found to have only about two-thirds of the normal life because of the loss of lubrication. Shielded ball bearings offer a partial solution to the problem but their biggest drawback is insufficient grease-storage capacity, especially in the types that are made to the same over-all dimensions as unshielded bearings.

It has been found impracticable to clean and relubricate ball bearings unless special equipment is provided in a suitable dust-free room and unless the work is done by properly trained personnel. In an emergency ball bearings can be cleaned with kerosene or some other suitable solvent, but in general this is unsatisfactory under field conditions. After the bearings have been soaked for several hours they may be spun by hand until all of the grease and dirt has been worked out of them. If they are spun by an air hose or other mechanical means the races are liable to damage by small particles being ground into the bearing surfaces.

In general, single-shielded ball bearings are preferable to the double-shielded type, particularly if the bearing mount is designed so that there is adequate shielding on the open side and if sufficient space is allowed on the other side for an adequate grease reservoir.

Proper lubrication of any bearing is essential. For low-temperature operation of ball bearings, any grease meeting Army-Navy Aeronautical Specification AN-G-3a has been found suitable; most lubricant manufacturers can furnish approved greases. For temperatures above 70° and even up to 100°C Andox C has been found satisfactory, although 100°C operation is not desirable. At low temperatures Andox C has a tendency to solidify. At very low temperatures (below -55°C) Univis 48 or an equivalent oil should be used, although it has a tendency to creep out of the bearings at higher temperatures. At present (1945) there is no lubricant that is satisfactory over the entire temperature range and it is necessary to decide which end of the range to favor and to choose the lubricant accordingly.

In practice it has been found necessary to service or replace motor ball bearings operating at room temperature at least every 1000 hr of operation for best results, and at least every 300 to 500 hr when operated at an ambient temperature of 70° to 80°C.

Oil-slinging disks or rings have been found desirable on all types of motors. These are knife-edge washers that rotate with the shaft and cause any oil or grease leaking from the bearing to be thrown out into the end bell by centrifugal force rather than to creep along the shaft and onto the commutator or winding.

The recent advent of high-temperature insulations such as Fiberglas and the silicone varnishes has permitted the construction of motors that can operate at greatly increased temperatures, but full benefit of the new materials cannot be obtained until good high-temperature lubricants are

developed. One of the most promising classes of lubricants is the silicone oils and greases, but to date (late 1945) they have not been satisfactory for use in standard ball bearings. Silicone-lubricated steel bearings score very readily and have short life. Better results have been obtained with special bearings having bronze races and steel balls, but these are not generally available at the present time. Active development work is continuing, especially on special additive compounds to improve the lubricating qualities of the silicones, and satisfactory high-temperature lubricants will probably be available in the future. It is likely that these lubricants will also be suitable for operation at very low temperatures, since the properties of the silicones change very little over a wide temperature range.

Special Features and Attachments.—In many cases the only thing that is "special" about a special motor is the provision of some integrally mounted feature that might otherwise be considered part of the associated equipment rather than of the motor. There is a great variety of such attachments; probably the most common are integral gear boxes and centrifugal governors, but the list also includes magnetically or centrifugally operated clutches and brakes, thermal relays to protect the windings or bearings against excessive temperatures, extra-long or doubly extended shafts, special mountings, and many other features that may be seen in various motor catalogues. No general rules can be made for specifying such special features, but a few of them are discussed in Sec. 11·6.

TYPES OF MOTORS

In the 1930's most small motors were of the universal a-c–d-c type or were split-phase, shaded-pole, capacitor-start, or capacitor-run a-c motors. Very few motors of other types were made in sizes smaller than $\frac{1}{8}$ hp, and small d-c and polyphase motors were almost unobtainable. The great demands of the war years for motors of all kinds forced a phenomenal development of specialized types, and today it may almost be said that there is no such thing as a standard fractional-horsepower motor, each model being designed to fit one particular application. With the change to peacetime production this situation is bound to change; many highly specialized types for which there is little demand will no longer be produced, and effort will be concentrated largely upon fewer types of more general applicability. In spite of this trend, however, there will be many types for which a steady demand will persist in sufficient volume to warrant continued production, and in the future many more types of motors will be available to the designer than there have been in the past.

The remaining portion of this chapter will be devoted to brief descrip-

tions of a number of the more important or more interesting types of motors, and of certain types of special attachments that are available as integral parts of small motors.

11·3. Direct-current Motors.—Direct-current motors in fractional-horsepower sizes or larger are usually designed to operate at 110 or 220 volts, or higher in the cases of large units or railway motors. Motors for shipboard operation may also be rated for 24- or 32-volt operation. Early aircraft motors operated at 6, 12, 24, or 27 volts, but later all but the 27-volt rating were practically abandoned. Aircraft motors range in size from midget 1-watt units (weighing 4 oz and occupying about 2 in^3) to integral-horsepower types that are considerably smaller and lighter than older units of the same ratings.

Standard Types.—Standard d-c motors are usually classified into series-, shunt-, and compound-wound types. Recently the permanent-magnet-field type has become important, and there are various special motors that do not fit easily into any of these classes.

Series motors are used where high starting torque is required and where poor speed regulation and high voltage sensitivity (speed varying as the square of the applied voltage) can be tolerated. The universal motor is a slightly specialized type of series motor, its principal distinguishing feature being the lamination of the field structure to reduce eddy-current losses when operated with alternating current. A series motor is the only type that is practical for a-c–d-c operation because of the requirement that the field be of low enough inductance to permit drawing the same magnetizing current in both a-c and d-c operation. As it is, the average universal motor will deliver about 10 per cent less power with alternating current than with direct current.

Series motors are ideal for fans and blowers, step-positioning devices, and other applications where speed is comparatively unimportant and the load is constant. They have poor speed regulation, short starting times, and draw very heavy starting currents when started directly across the line, so that starting-current–limiting devices must often be used. In the larger sizes, series motors must never be fed full voltage when not connected to a load because the excessive no-load speed is likely to cause destruction of the motor through the high centrifugal forces on the rotor windings. Certain types, however, are designed to withstand these stresses, and are useful when high rotational speeds are required. Series motors are particularly well adapted to speed control by series resistors or rheostats and by centrifugal contact-making governors.

Shunt motors have from low to medium starting torques and fairly good speed regulation, that of a good motor being in the neighborhood of 10 to 20 per cent. The speed is roughly proportional to the impressed voltage and is easily regulated over a considerable range by a rheostat

in series with the field; the speed regulation becomes poorer with decreasing field current, and care must be taken never to permit the field circuit to be opened while the armature is excited since the motor will either run away or will stall and burn out. Shunt motors are suitable for antenna drives and other applications requiring better speed regulation than can be obtained with series motors.

Compound motors have both shunt and series fields, which allow considerable latitude in design. They can be designed to have a "drooping," a flat, or a rising speed characteristic (full-load speed less than, equal to, or more than no-load speed). Motor-generator sets often use compound motors that are designed to approximate series-motor characteristics in order to get high starting torque and then short-circuit the series field by a centrifugal switch or a relay in order to get the better speed regulation of a shunt motor after the unit is up to speed. Compound motors with flat or rising speed characteristics must usually be started with the series fields short-circuited in order to prevent the high starting current through the series field from overcoming the shunt field, causing the motor to start in the wrong direction with a resulting excessive input current. The series windings in some compound motors may have as few as one turn; in other types they may have sufficient turns so that the motor may be run as a shunt motor, with the "series" field in parallel with the shunt field. A typical small unit, that may be used either as a motor or a generator, is shown in Fig. 11·1.

Permanent-magnet Motors.—With the advent of the various Alnico magnetic materials, permanent-magnet-field (PM) motors and generators have again come into common use. PM motors have characteristics similar to those of shunt motors. A number of types have been placed on the market, the motors being rated from one to several hundred watts and the generators up to 5 kw. Several of the smaller types are shown in Figs. 11·2, 11·3, and 11·4.

The smaller PM motors are produced as plain motors for direct connection to fans, blowers, etc., and also with integral gear boxes with very high reduction ratios (1000/1 to 10,000/1). Some models also have centrifugal governors for accurate speed regulation. Spur gearing is generally used because of its high efficiency. Geared midget PM motors are commonly used in positioning devices for remote tuning, trimming, antenna tilting, etc. Two of the chief advantages of a PM motor are its ease of speed control by controlling armature current and its easy reversibility by reversing the polarity of the feed voltage. Its chief disadvantage is that overload or plugging may cause loss of field or shifting of field poles.

The principal use of PM units in the Radiation Laboratory has been as generators, both a-c and d-c. The d-c generators have been designed

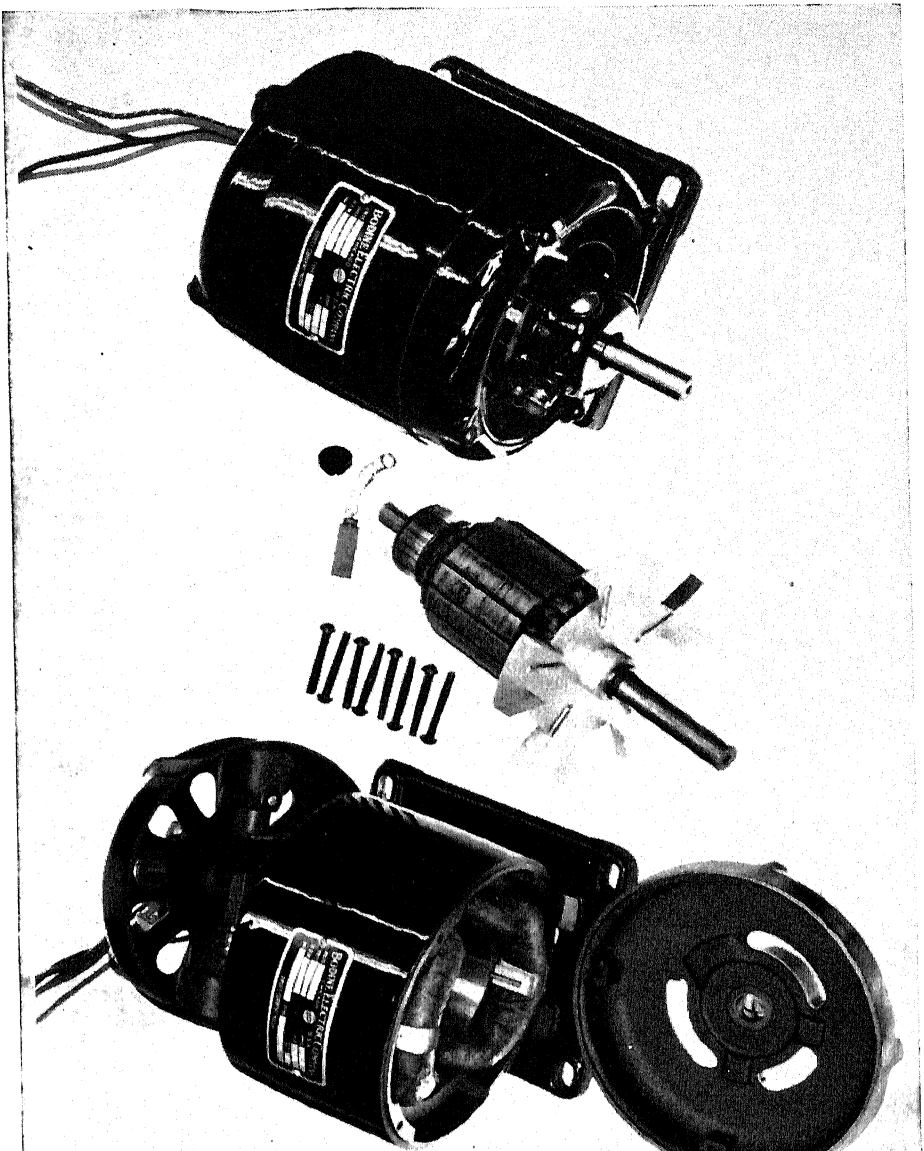


FIG. 11·1.—Bodine compound-wound d-c motor or generator: 115 volts d-c, $\frac{1}{8}$ hp, 1725 rpm, sleeve bearings.

for special characteristics such as linearity and constancy of the speed-voltage characteristic, low ripple, etc. They are often used as tachometers and in various forms of computers. Alternating-current units are available with 1-, 2-, and 3-phase outputs, the single-phase being the most common.

The design of an accurate PM d-c tachometer generator involves attention to a number of details if the best results are to be obtained. One of the most important means of eliminating erratic shifts in output

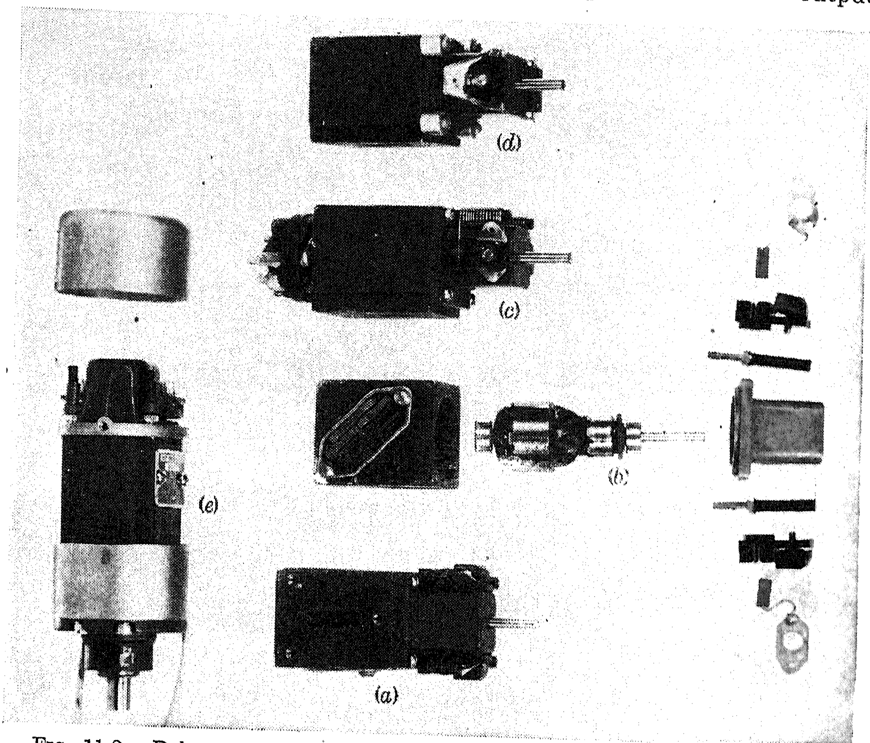


FIG. 11·2.—Delco midget PM motors. (a) Standard type; (b) standard type, disassembled; (c) standard type with Lee governor; (d) with hinge-type brushes for tachometer use; (e) with integral gear-reduction unit and brush cover.

voltage is the provision of hinge-type brush holders, as mentioned in Sec. 11·2 and shown in Fig. 11·5. Other important features are the use of heavy shafts and high-grade ball bearings, silver commutators with many more bars than normal for the size, and armature laminations skewed to reduce slot-lock and ripple to a minimum. Figure 11·6 shows an experimental tachometer generator involving these features.

Special D-c Motors.—There are many more or less specialized types of d-c motors. Most of these are of too restricted application to warrant mention here, but there is one common type that is of general application.

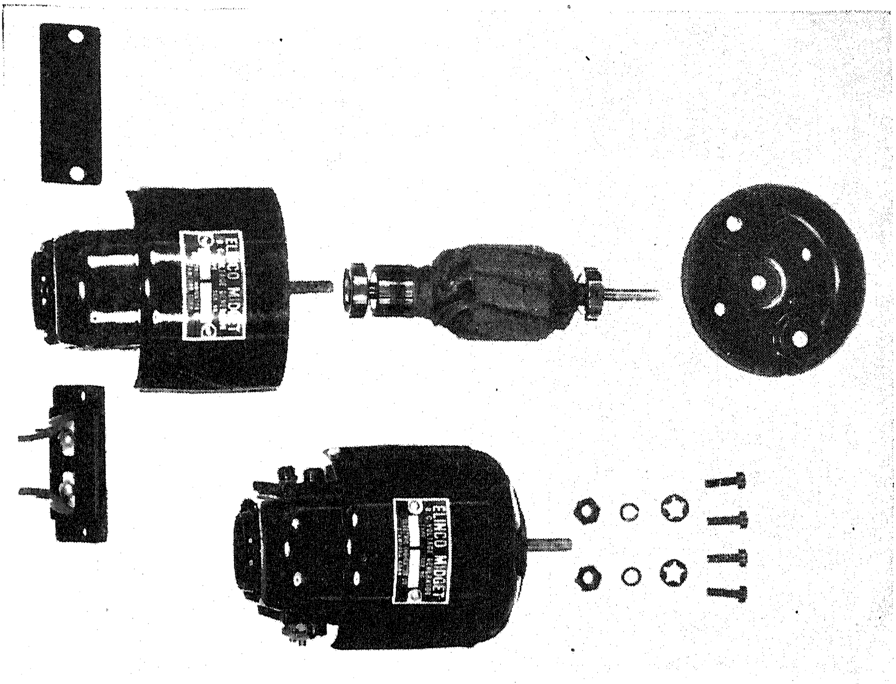


FIG. 11·3.—Elinco PM d-c generator assembled and disassembled: generally used for tachometer and computer applications; output about 37 volts at 1800 rpm; finger brushes, as shown, intended for speeds under 2000 rpm; for higher speeds conventional square brushes are recommended to reduce brush bouncing.

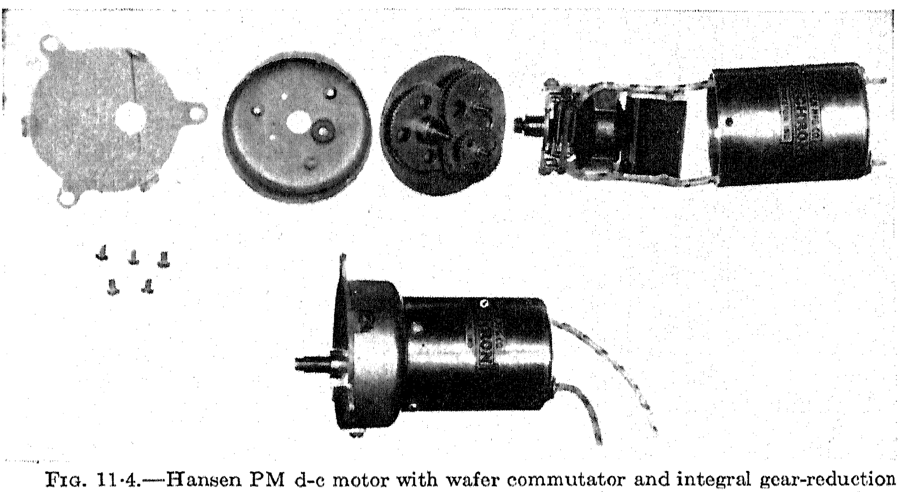


FIG. 11·4.—Hansen PM d-c motor with wafer commutator and integral gear-reduction unit: made for 6-, 12-, or 27-volt service with output speeds of 1, 3, or 10 rpm; used for remote-positioning applications, etc; also furnished without gear box for fan service, or with centrifugal friction speed governor.

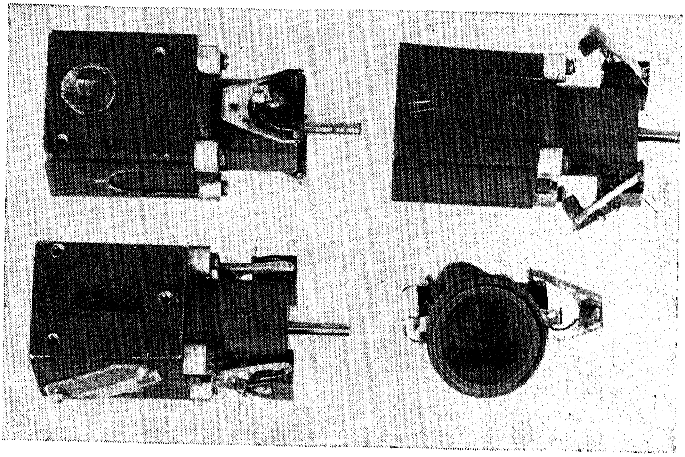


FIG. 11·5.—Delco midget PM motors with special brushes for tachometer service: hinge-type brush mounting prevents voltage variations due to changes in position of brush axis.

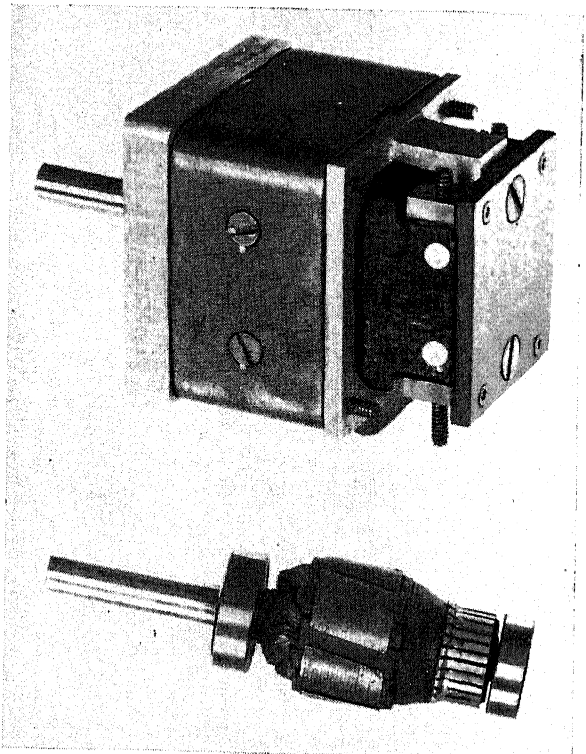


FIG. 11·6.—Experimental tachometer and spare armature: hinge-type brushes, heavy shaft and bearings, many-section silver commutator, and armature laminations skewed to reduce slot lock and ripple.

This is the so-called "split-field" motor intended for reversing service. In its commonest form it is a series motor with two oppositely poled field windings. One end of each field winding is connected to one armature brush and leads are brought out from the other brush and from the two free ends of the field windings. Connection of the line between the brush lead and one field lead will cause the motor to run in one direction with full power; connection to the other field lead will reverse the rotation, so that the motor can be controlled remotely by a single-pole switch and only three leads need to be run to it. The split-field principle can be applied to other types of motors, but the complications involved are such that very little is gained over the use of conventional windings.

11·4. Alternating-current Motors. *Standard Types.*—Wartime developments in the a-c motor field have been relatively fewer than in the d-c field, both because a-c motors are less important in military equipment and because the prewar types of a-c motors required less work to adapt them to wartime requirements. In the small a-c motor field the most important types are the universal motor (previously discussed), the split-phase, the shaded-pole, and the capacitor motors. Polyphase, repulsion and repulsion-induction, and other types are seldom made in small sizes, with certain exceptions to be discussed later.

With the exception of the universal motor and certain types of a-c commutator motors, all of which have essentially series-motor characteristics, the speeds of a-c motors depend primarily upon the frequency and the number of poles, and can be controlled with difficulty if at all. Where speed control is necessary and commutator motors cannot be used it is necessary to use some type of variable-speed mechanical transmission. One exception to this rule is the wound-rotor polyphase induction motor, but this type is seldom or never made in fractional-horsepower or smaller sizes.

Split-phase motors are probably made in greater numbers than any other type of a-c motor. They have high starting torque and good speed regulation and are comparatively inexpensive, but their starting current is high, they do not handle high-inertia loads well, and they cannot be reversed while running but must be brought to a stop first. In addition, the centrifugal starting switch is the source of abundant trouble, especially in corrosive or dusty atmospheres, and the starting winding is usually made of such small wire that frequent starting and stopping quickly burns it up.

Capacitor motors are somewhat better than split-phase motors in many respects, but are more expensive. They have lower starting currents and usually operate more smoothly and quietly than split-phase motors. The capacitor-start motor uses a centrifugal starting switch; the capacitor-run motor does not but has very low starting torque and is most

suitable for light loads such as fans and blowers. A typical low-power synchronous capacitor-run geared motor is shown in Fig. 11·7. Small capacitor-run motors with two identical windings in space quadrature and with low-inertia squirrel-cage rotors of high resistance are suitable for contact-type servo applications, but are gradually being replaced by similar types intended for electronic servo use. Capacitor-start-and-run motors use a large capacitor to get high starting torque and then cut it out by means of a centrifugal switch; they run with a smaller capacitor. The

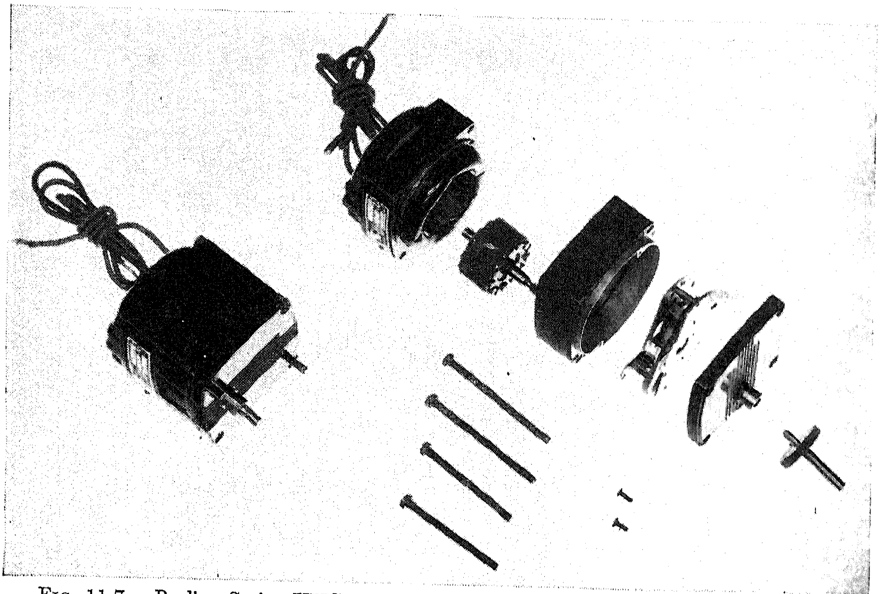


FIG. 11·7.—Bodine Series KYC-22 synchronous capacitor-run a-c motor with integral gear-reduction unit: output from $\frac{1}{8}$ to 1 watt, various output speeds from 1 to 1800 rpm; 115 volts, 60 cps; also made in nonsynchronous type with about twice the output power.

large condenser is rather expensive and the starting switch is likely to give trouble.

Shaded-pole motors are in some respects the simplest and cheapest type of induction motor, but are only made in small sizes since their efficiency is seldom over 20 per cent and they have very poor speed regulation. They are made both in the slug type which will run in only one direction and in the two-coil type in which one or the other shading coil is short-circuited in order to get the shaded-pole effect and to reverse the rotation. The two-coil type is usually made only in sizes below $\frac{1}{50}$ hp. A typical modern shaded-pole motor is shown in Fig. 11·8.

Small timing and clock motors such as those made by Haydon and Hansen are of the shaded-pole type with multipole salient-pole rotors; they run at synchronous speeds of 600 to 900 rpm. Telechron motors

are also of the shaded-pole type but have ring rotors of hard steel and run at 3600 rpm. Most clock motors are equipped with integral gear boxes giving output speeds of from 60 rpm down to as low as 1 revolution per 24 hr. They are all in the "flea-power" class, with inputs of from 2 to 12 watts.

Repulsion-start induction-run motors have high starting torques and low starting currents but are expensive and are not made in small sizes. Brush-shifting commutator-type a-c motors of the repulsion-induction type are made down to about $\frac{1}{4}$ hp, but are expensive and have rather poor speed regulation. Their speed can be controlled by shifting the brush position, and they are often used for blowers, fans, coil winders, and other devices for which a variable speed is necessary.

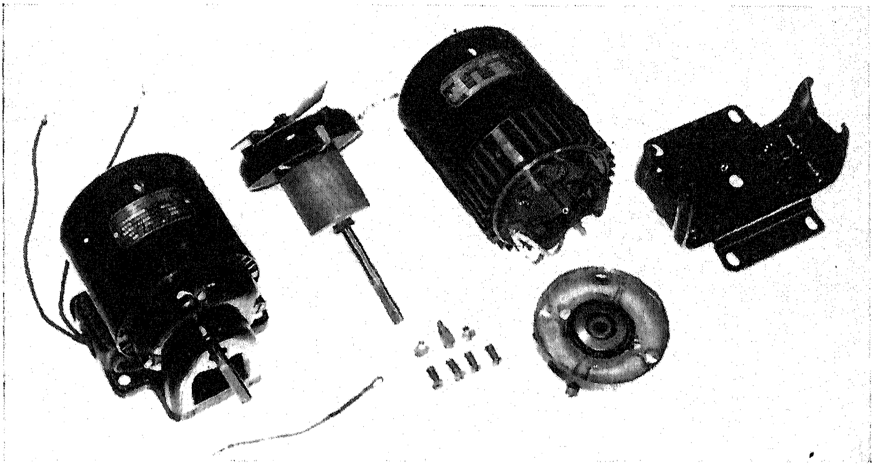


FIG. 11·8.—Redmond shaded-pole a-c motor: 115 volts, 60 cps, $\frac{1}{35}$ hp, 1200 rpm; resilient mounting, external fan, cooling fins, and shroud; principally used for fan service.

High-frequency Motors.—The rapid increase in the total connected load of airplane electrical systems and the introduction of various electronic devices that demanded a supply of a-c power forced the adoption of the (nominal) 400-cps 120-volt aircraft power system. This in turn created a demand for a-c motors that would operate at the new high frequencies, and led to the development of a number of different types. Those developed by the Eastern Air Devices Corporation were typical; two models are shown in Figs. 11·9 and 11·10. The type J31C motor shown in Fig. 11·9 is particularly interesting since it was so designed that with a No. 2 L-R blower as a load it runs at an approximately constant speed of 6000 rpm for all input frequencies from 400 to 1800 cps. With other than the design load, of course, the speed varies somewhat with frequency. Operation in the higher position of the frequency range may be improved by using somewhat smaller capacitors than those

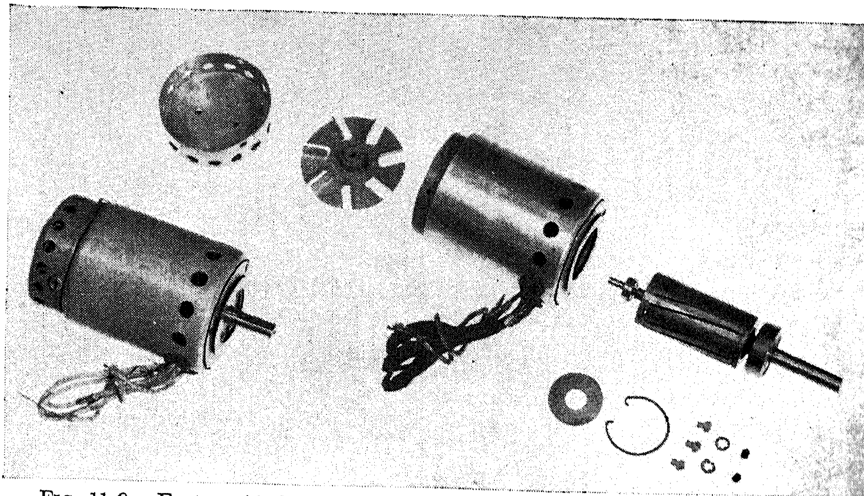


FIG. 11·9.—Eastern Air Devices variable-frequency capacitor-run a-c motor: with fan load, motor runs at nearly constant speed of 8000 rpm and output of $\frac{1}{100}$ hp at all frequencies from 400 to 1800 cps; also made for single-frequency operation.

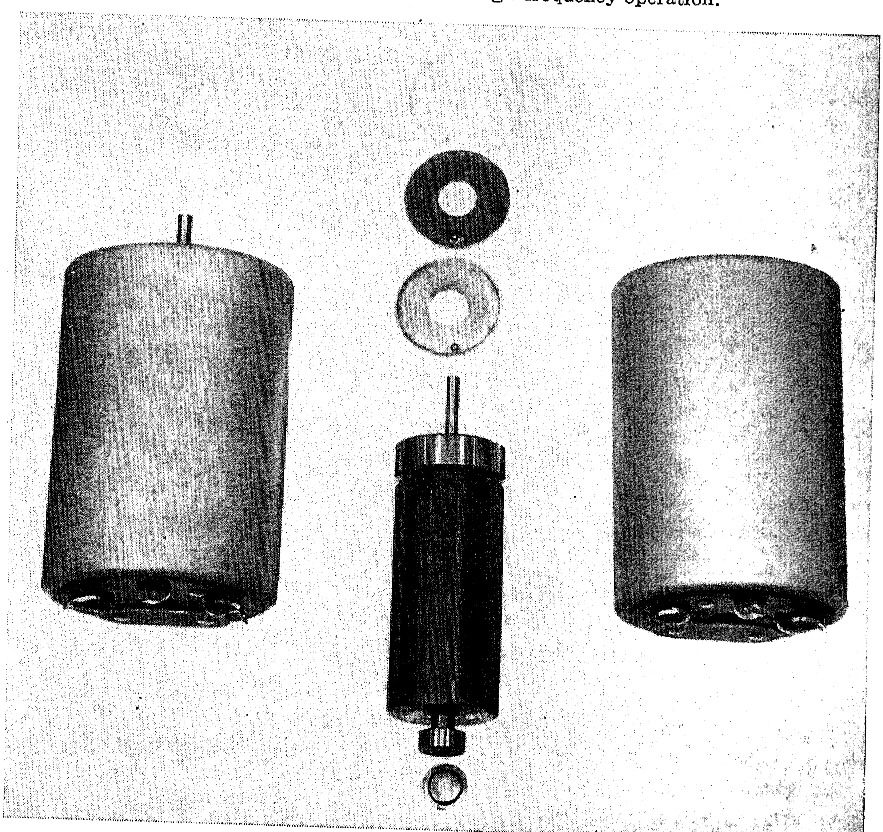


FIG. 11·10.—Eastern Air Devices 3-phase 400-cps synchronous motor: $\frac{1}{100}$ hp, 115 volts, [illegible]

required for operation at 400 cps. The motor of Fig. 11·10 is a straight 3-phase induction motor with a milled squirrel-cage rotor for synchronous operation. Larger high-frequency motors are generally squirrel-cage 3-phase motors; a number of very compact high-speed high-output types have been developed for driving the propellors of wind-tunnel model airplanes and for gearless drives in high-speed machine tools. Some of the largest units have outputs of 30 hp or more in sizes of about 6 in. diameter by 18 in. long; water-cooled windings must be employed to keep the unit from burning up. High-frequency motors of $\frac{1}{10}$ hp or less are usually of the capacitor-run type.

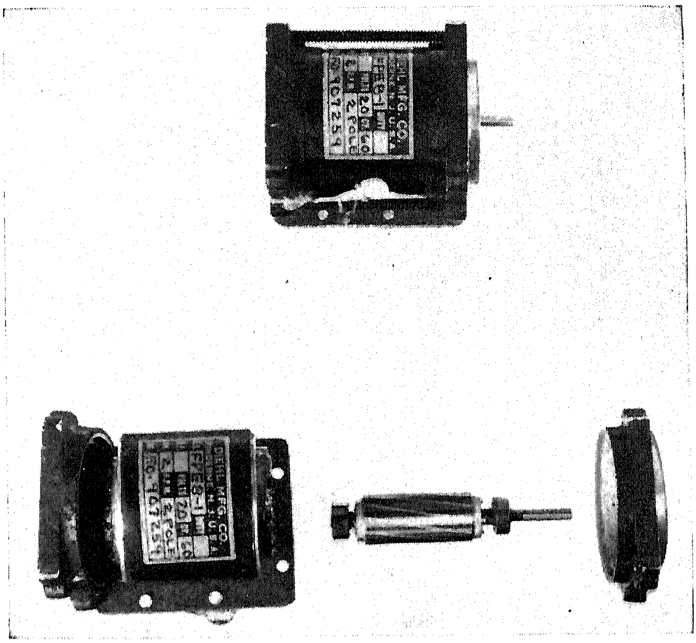


FIG. 11·11.—Diehl 2-phase low-inertia a-c motor: type FPE8-1, 20 volts, 60 cps, 2-pole; useful for very low-power servo applications.

Low-inertia Motors.—One class of a-c motor that has become important within the last few years is the low-inertia servo motor. These motors, of which those shown in Figs. 11·11 through 11·13 are typical, are usually small or medium-sized a-c motors with two (usually identical) windings in space quadrature on the stator and squirrel-cage rotors that are made long and of small diameter to reduce the moment of inertia. The rotor resistance is usually high in order to improve the starting torque; this is permissible since these motors normally run well below synchronous speed. A somewhat different a-c servo motor is shown in

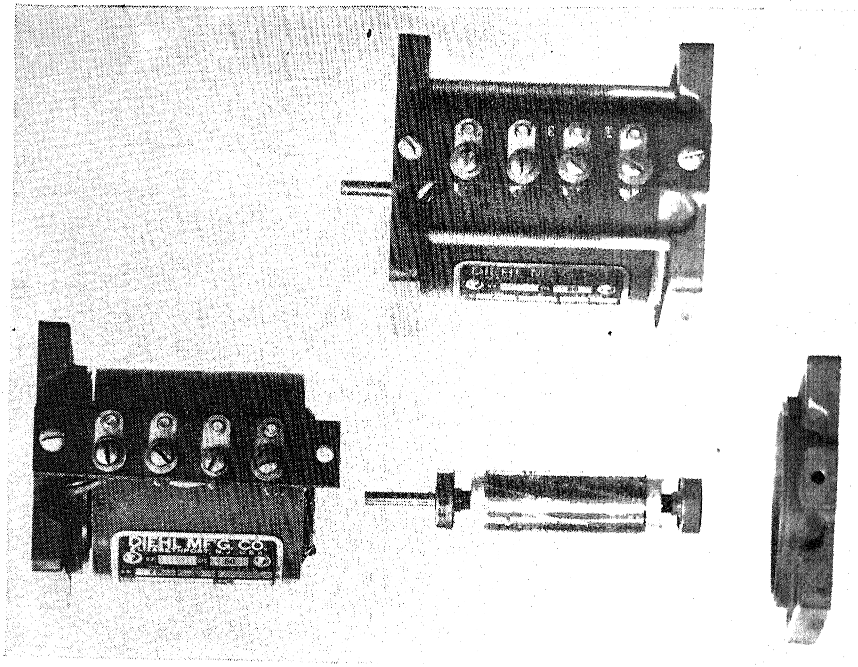


FIG. 11·12.—Diehl 2-phase low-inertia a-c motor: type FP25-2, 22 volts, 60 cps, 2-pole; useful for instrument servo drives.

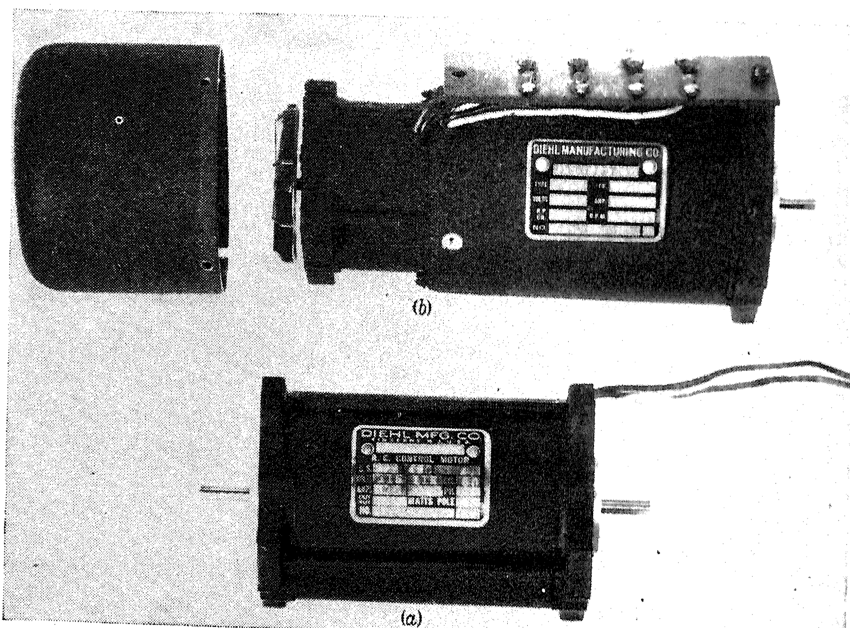


FIG. 11·13.—Diehl 2-phase low-inertia a-c motors: (a) type FPE49-4, 115 volts, 60 cps, 2-pole, mechanical output 11 watts; (b) identical unit except furnished with cooling fan driven by separate motor, output 22 watts.

Fig. 11·14. In this motor the length-to-diameter ratio is not so great as in the previous examples, but the rotor is furnished with a small drag-cup that rotates in the field of a permanent magnet in the end bell. This field causes a drag on the rotor that is proportional to velocity and damps out high-acceleration "jitter" of the rotor.

These 2-phase motors may be used in a wide variety of circuits; in one of the simplest and most satisfactory, one phase is continuously excited from the a-c line and the other is fed from a servo amplifier. If the error signal is alternating current of line frequency, as when it comes from a

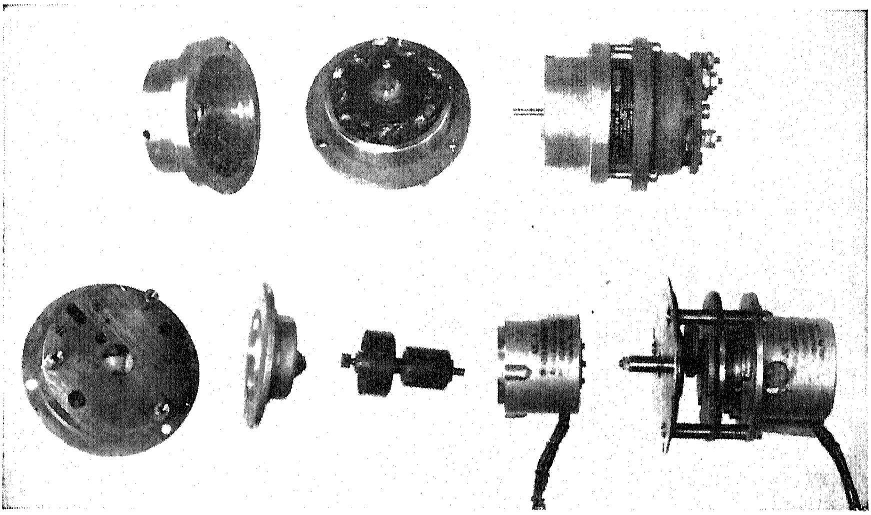


FIG. 11·14.—Pioneer-Bendix type CK-5 servo motor: squirrel-cage rotor and drag cup used for damping; small Alnico damping magnet is mounted in end bell; integral gear-reduction unit.

synchro control transformer, the amplifier merely serves to raise its power level to the point required by the motor. If the error signal is direct current a suitable modulator unit such as a Brown vibrator (see Chap. 13) may be used. The necessary 90° time-phase shift may be introduced in the error signal circuit, in the amplifier, or in the fixed-phase circuit. Servomechanisms of this type have been extensively used in equipment designed by the Radiation Laboratory, especially in fire-control computers and in similar applications. They are discussed at length in Vols. 21 and 25 of this series.

Since one criterion of the suitability of a motor for servo applications is its torque-to-inertia ratio, several manufacturers have attempted to reach the highest possible values of this ratio by using the principle of the induction-disk watt-hour meter in the form of the drag-cup motor. Typical drag-cup motors are shown in Figs. 11·15, 11·16, and 11·17. These motors are used in much the same fashion as those just described.

The very light aluminum rotors have small moments of inertia, but the drag-cup motor as a class has a rather low output for a given total weight. The drag-cup construction, however, does make an excellent a-c tachometer; if one winding is excited by single-phase alternating current, a single-phase voltage that is accurately proportional to the velocity of the rotor will appear on the other winding. This permits multiplying two quantities, one of which is in the form of an a-c voltage and the other in the form of a shaft speed. The product is in the form of an a-c voltage. Such a device has many applications.

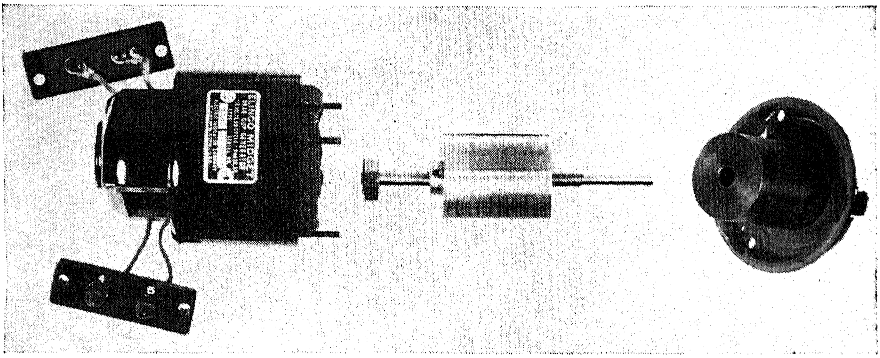


FIG. 11·15.—Elinco midget drag-cup generator, type B-68: 110-volt 60-cps input, 60-cps output proportional to speed; used as a-c tachometer.

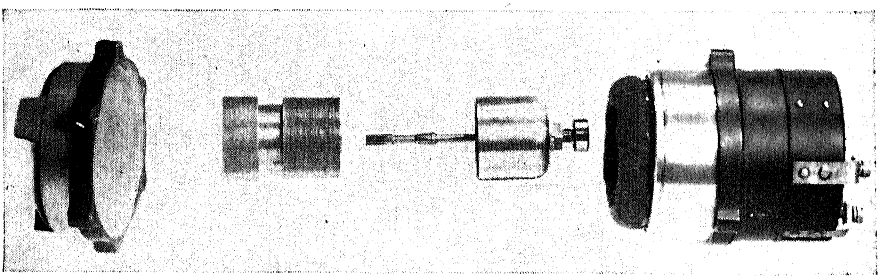


FIG. 11·16.—Kollsman a-c drag-cup tachometer or motor: used as tachometer or very low-power servo motor.

11·5. Special Types of Motors.—Most "special" motors differ from standard types in having nonstandard dimensions or mountings, in having windings modified for operation at a nonstandard voltage, or else in the provision of some special attachment or device not ordinarily furnished with a motor. There are certain types of motors whose internal structure or mode of operation differs from standard types; most of these are too specialized to warrant discussion here but one or two types may serve as examples of special motors.

Many specialized motor types include elements of two or more motors or generators within one frame. They may often be distinguished from

motor-generators only in that the output of interest is mechanical and that the electrical output is incidental to speed control or some similar purpose. An elementary example would be a large motor (of any type) with a built-in tachometer generator. Such a machine would be a special motor, but it would also be highly uneconomical since it would be much simpler and cheaper to attach a standard tachometer generator to a standard motor by a suitable mounting device.

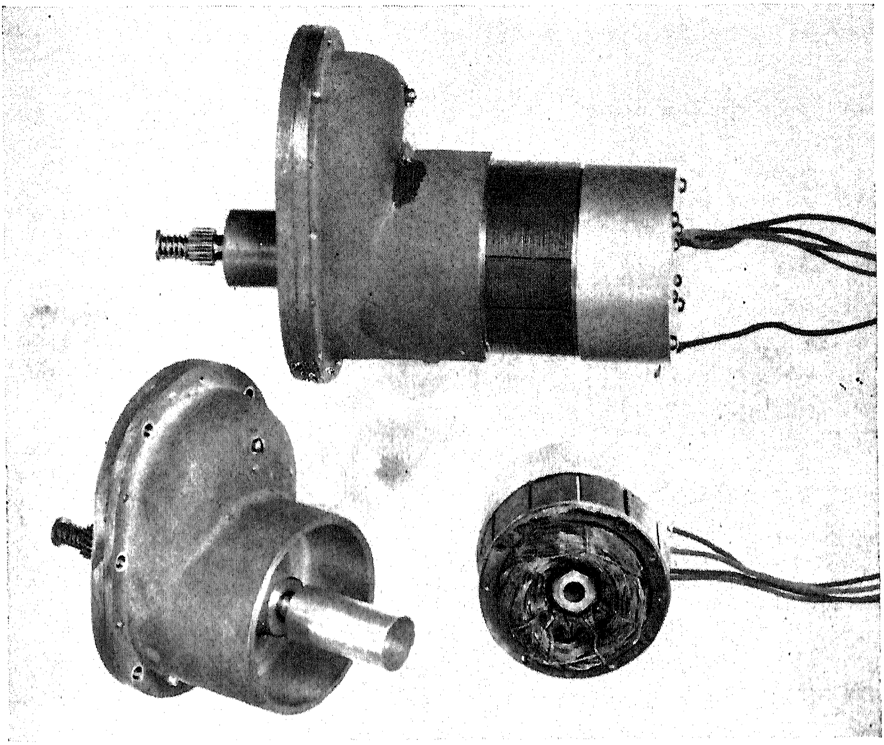


FIG. 11·17.—Bell Telephone Laboratories drag-cup motor: has integral gear box and spring-loaded antibacklash output pinion; used in a-c servo applications.

For particular applications, however, especially in airborne equipment where weight and size are more important than cost and standardization, it is necessary to design multifunction machines. One example is a d-c motor with accurate speed control, made by the Bell Telephone Laboratories. It is a descendant of the old Stoller system motor originally used for projector and turntable drives in the early days of talking motion pictures. It consists essentially of a normal d-c motor with a small coil at one end embedded in the face of one pole piece. A portion of the rotor opposite this coil is milled to give salient poles and the small coil has a voltage induced in it just as in the windings of an inductor alternator.

This voltage is passed through a frequency discriminator and rectifier circuit, giving a d-c output that varies linearly with frequency over a small range; this d-c voltage is amplified and fed back to the control field of the motor. In one sample the motor speed was held to 7200 ± 3 rpm over the entire rated range of loads and input voltages. Still closer regulation could be accomplished by using a discriminator of greater slope, such as a quartz-crystal filter.

Another type of special motor is used in the Electro-Tie system, manufactured by the Electrolux Corporation. A typical Electro-Tie motor is shown in Fig. 11·18. This motor is essentially a conventional

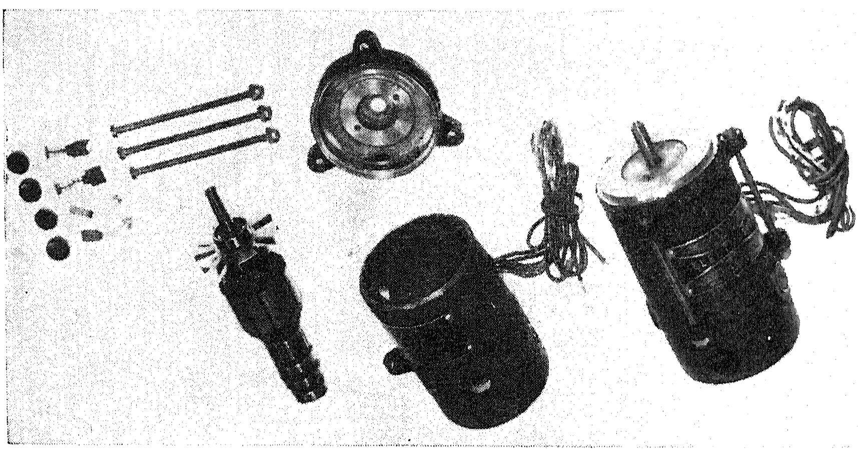


FIG. 11·18.—Electrolux "Electro-Tie" or "d-c synchronous" motor: 27-volt d-c input, 2 slip rings bringing out taps on armature winding; interconnection of corresponding slip rings on all motors of a system serves to keep motors in step.

aircraft motor to which two slip rings have been added. The slip rings are connected to two opposite points on the armature winding, so that as far as the slip rings are concerned the motor looks like a conventional rotary converter. If corresponding terminals of two or more a-c–d-c motors are connected together the a-c terminal voltages will be respectively equal if and only if the motors run in exact synchronism. Any lead or lag of the position of one armature will change the generated a-c voltages and currents will flow in the a-c leads in such a direction as to restore synchronism between the several armatures. The synchronizing action is exactly the same as that of a conventional synchro, except that it occurs only when the fields are excited and the armatures are rotating. The synchronizing action would be weak at very low speeds because of the small induced voltages, although there is also a slight synchronizing action due to the d-c voltage drops in the armature windings. In normal operation initial synchronization is accomplished by a set of relays which

applies d-c voltage to the fields, then momentarily to the a-c terminals, thereby pulling all the armatures into corresponding positions with respect to the fields. The direct current is then removed from the a-c terminals and applied to the commutator brushes and the motors start and run in synchronism. In stopping, the reverse operation takes place; the direct current is removed from the commutator brushes and applied to the a-c leads, which gives almost instantaneous stopping and leaves the motors in step. The direct current is then removed from the whole system.

The Electro-Tie system was originally applied to the control of the flaps on an airplane, and then was adapted to the carburetor controls on a four-motored plane. The system is capable of numerous variations; one motor can be run at a faster or slower speed than the others, limit switches can be used, and all ordinary d-c motor controls can be applied to the system for reversing, speed control, etc. The load on any one motor can be varied from zero to overload without loss of synchronism. Any number of motors may be operated together.

In certain applications it is desirable to use a motor that is capable of operating at two or more fixed speeds with electrical selection of the speeds and fairly good speed regulation at each speed setting. With a-c motors this is most simply accomplished by pole changing. With d-c motors there are several possible methods. One is to provide a series motor with an auxiliary shunt field. One type tested gave a speed ratio of 2 or 3 to 1; as a shunt motor the operation was fair but as a series motor the speed regulation was poor, as might be expected. For certain applications this might not be a serious disadvantage. Another method is to provide a shunt motor with two commutators and two independent armature windings; the commutators are connected in series for low-speed operation and in parallel for high speed. A speed ratio of 2 to 1 is obtained, with good regulation at both speeds. Such a motor, made by the John Oster Manufacturing Company, is shown in Fig. 11·19. A similar unit is made by Speedway.

There are many variations of field windings that place a d-c motor in the "special" category. The provision of duplicate series fields, referred to above, to allow instantaneous two-wire reversing is so common as hardly to merit the term "special." Many motors have additional control-field windings, particularly when they are to be used for servo applications; control fields on dynamotors and motor-generators are also very common and several examples are to be found in Chap. 12.

11·6. Motor Attachments and Auxiliaries.—Many special motors are special only because of some built-in or integrally attached device that is not actually a part of the motor but is most conveniently incorporated in its structure. A wide variety of motor attachments and auxiliaries is

available, as a perusal of any motor catalogue will show. Many of these need not even be mentioned here, but there are certain attachments that are of sufficient importance to warrant discussion.

Many special motor features are in the nature of mechanical modifications rather than attachments. Special mounting devices, such as the

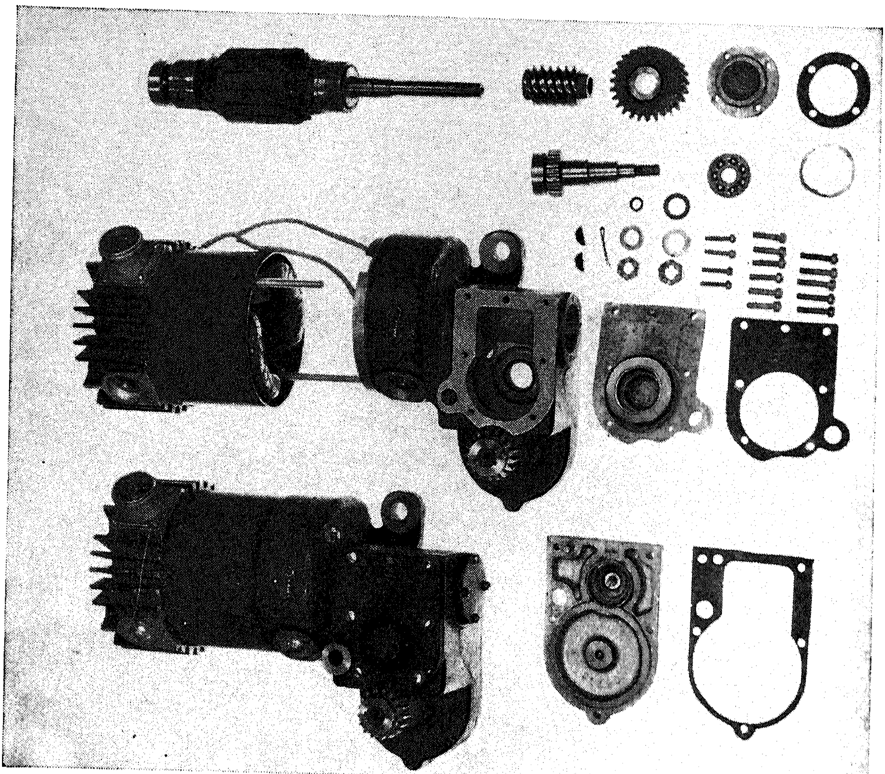


FIG. 11·19.—Oster double-commutator two-speed d-c shunt-wound motor: 27 volts, $\frac{1}{20}$ hp; speed change obtained by series or parallel connection of the two armature windings.

resilient mounting shown in Fig. 11·8, and various tripod or flange mounts are available for almost any motor. Extra-length or double-extended shafts are also needed occasionally. Another special shaft that is sometimes useful is the hollow shaft, often used in wood-lathe spindle motors and other machine tools. A standard hollow-shaft motor was adapted to the requirements of a conical-scanning radar antenna by the Radiation Laboratory, and was later produced in considerable numbers by the General Electric Company. It consisted of a conventional a-c motor plus a two-phase permanent-magnet-rotor alternator used for generating a reference voltage for the antenna servo circuits, both mounted on a large hollow shaft. Either a concentric line or a round waveguide could be

run through the shaft from a rotating joint in the rear to the spinning antenna in front of the reflector. The motor was mounted at the rear of the reflector.

Other features are attached to the motor structure without major modifications of the latter. These features include special connectors or terminal boards, boxes and conduit fittings, switches, limit switches (usually only on gear motors with low output-shaft speeds) and thermostatic switches to protect the windings or bearings from excessive temperatures.

The most important motor attachments, however, are probably integral gear boxes, clutches and brakes, and speed governors. These features warrant discussion at some length.

Gearing.—Nearly all important types and sizes of motors may now be obtained with integrally mounted gear boxes of various reduction ratios. Cheap motors usually obtain high ratios by using one or two worms and worm gears. The worms are usually unhardened steel and the worm gears, laminated plastic. Such gear trains are inexpensive and operate quietly, but the efficiency of a worm-gear train is low and the plastic gears are so weak that high torques cannot be obtained from the output shafts. Worm-gear efficiencies vary with size, type, and precision of manufacture, but usually lie between 20 and 50 per cent for small gears, while 60 to 80 per cent is considered only fair for spur-gear trains and 90 per cent can be obtained in many cases with little trouble. The higher-quality motors and many of the very small ones consequently use spur gearing. It is usually found that only one additional pair of gears is required in a spur-gear train to get the same reduction as for a worm-gear train, except for very high ratios.

It should be pointed out in this connection that when a gear train is used with a high-inertia load or under conditions of frequent reversal or other high accelerations an irreversible device such as the usual worm drive must not be used because the resulting high tooth pressures will cause immediate damage or destruction of the train. Spur-gear trains are reversible and can easily be designed to take the stresses encountered in such service. It is often possible to use some sort of cushioning device such as a slip-clutch or spring coupling between gear box and load.

Many of the motors with worm reduction gears are intended to run in only one direction and the gear boxes provide for taking up the thrust of the worm in forward rotation only, so that serious wear and friction will result if they are run backward. In addition, practically all series motors with integral worm-gear reducers have their brushes set for best operation in the forward direction, and have poor speed regulation and relatively low power when run backwards.

Unless spring-loaded split worm gears or similar devices are used the

motors; the brake is normally "on," being held against the drum by a strong spring. The brake solenoid winding is connected across the motor terminals so that when the motor is energized the brake is released and allows the motor to run free; when the current is cut off the brake is applied and brings the motor to a quick stop and holds it in position. In some applications in which the inertia of the motor armature would delay this action too much a clutch is also provided. In the aircraft

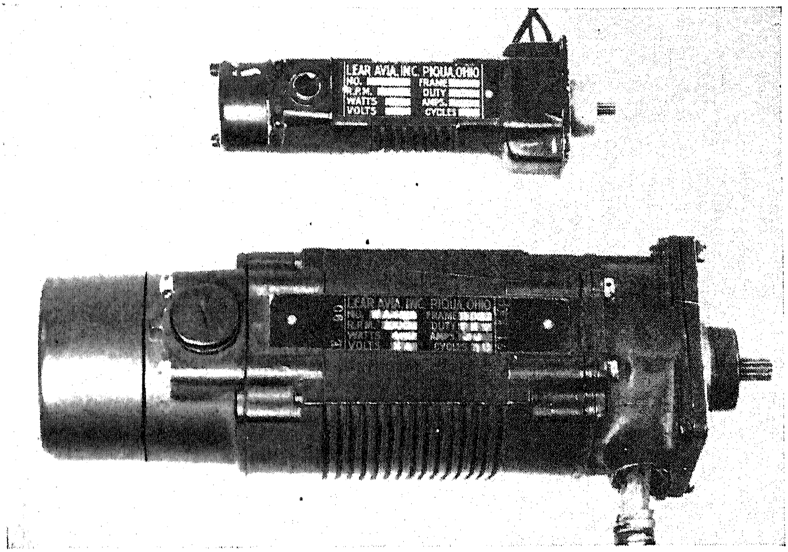


FIG. 11·21.—Lear Avia aircraft positioning motors: 27-volt d-c input, integral magnetic clutches and brakes for instant start and stop, split-field reversing, high output, intermittent duty; used for operating bomb-bay doors, positioning cowl flaps, and similar applications on airplanes.

positioning motors of Fig. 11·21 the output shaft is connected to a disk that is normally held outward against a stationary braking disk by a coil spring. When the motor is energized the disk is drawn inward by a solenoid against a driving disk on the end of the armature shaft. The moment of inertia of the driven disk is small and the output shaft stops almost instantly on deenergizing the motor and solenoid. These motors have been used for operating machine-gun ammunition boosters, etc., for which an overshoot is undesirable. There are many modifications of this construction, some omitting the clutch or the brake and some adding reduction gearing, limit switches, or other auxiliaries.

When high-inertia or "sticky" loads are encountered a modification of the clutch motor is often useful. In one form this includes a centrifugal switch that delays throwing in the clutch until the armature is up to speed; the full rotational energy of the armature is then available to kick the heavy load free. In a much older and somewhat simpler modification

backlash of a worm-gear reducer is usually much greater than that of a well designed spur-gear unit. The use of spring loading will reduce the efficiency of a worm gear still further below that of a spur-gear train of equivalent ratio and load capacity.

A variant of the gear motor is the motor with an integral variable-ratio mechanical transmission, with or without additional gear reduction.

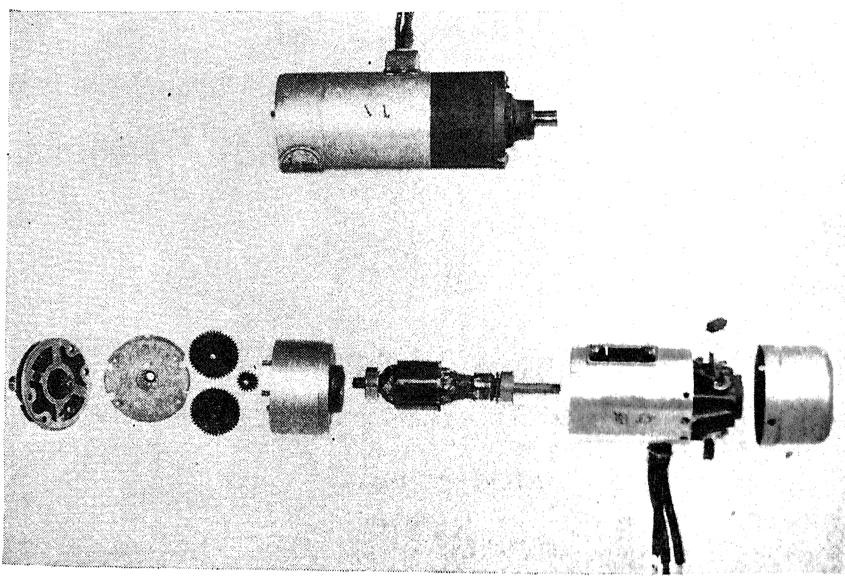


FIG. 11·20.—General Electric and Delco d-c aircraft motors with integral gear boxes: 27-volt input, split-field reversing.

Several small units of this type have appeared on the market, most of them intended for laboratory use in driving stirrers, etc., but most variable-speed motor drives are in the integral-horsepower class. They are useful for driving machine tools, plastic-extruding machines, and many other applications requiring precise control of motor speed. A line of inexpensive units with motors of ratings from, say, $\frac{1}{50}$ to 1 hp and really high-quality rugged mechanical variable-ratio speed reducers that could be accurately and reproducibly adjusted would be useful in many applications.

Various gear-reduction units are shown both whole and disassembled in several of the pictures of this chapter. Typical small aircraft gear-motors are shown in Fig. 11·20.

Clutches and Brakes.—Many positioning devices require motors that start and stop almost instantly, and to satisfy this demand a number of types of motors have been produced that have integral magnetic clutches and brakes. Magnetic brakes have long been used on crane and elevator

the same result is obtained by the use of a centrifugally operated mechanical clutch; this device was formerly incorporated into fractional-horsepower shaded-pole motors to compensate for their very poor starting torque.

Speed Governors.—One of the most important motor attachments has come to be the centrifugal speed governor. The development of satisfactory governors has done much to revive the use of the series motor, which has several excellent characteristics but is handicapped by poor speed regulation. These governors are also applicable to certain other types of motors, although usually with less advantage than in the case of the series motor.

One of the simplest governors is purely mechanical, being essentially a centrifugal brake. Mechanical governors are used on many types of phonographs, dictating machines, etc., and if properly designed and adjusted will give excellent service. They are subject to mechanical troubles, however, and if dirty, dry, or out of adjustment may introduce "wows" or other variations in the speed of the motor. A very compact type of mechanical governor is furnished with some models of the midget Hansen motor of Fig. 11·5. In this type, fiber slugs mounted on the armature shaft are thrown outward against spring pressure by centrifugal force and drag on the inner surface of a stationary brass cup. In general, however, mechanical governors are unsatisfactory for critical applications, and since they act solely as "lossers" they are not applicable to motors above the "flea-power" class.

Another possible method of controlling motor speed is analogous to the centrifugal governor of a steam engine, which closes the throttle and reduces the power input to the engine when the speed exceeds the desired value. This throttling action may be either gradual, as by a partial closing of the valve, or it may be an on-off type of control. The gradual closing method is exemplified by various electronic speed controls, such as the Bell Telephone Laboratories system referred to in Sec. 11·5, and by the Holtzer-Cabot carbon-pile speed governor described in Chap. 12. The on-off method is exemplified by the Lee governor and various other contact-making devices.

Most governor-controlled motors on the American market use the Lee governor, manufactured by the Lee Engineering Company of Milwaukee. This is a centrifugal vibrating-contact type of governor that is usually (but not necessarily) mounted on the end of the motor shaft. It has two contacts mounted on leaf springs, the inner one being adjustable either by a screw bearing on its spring or by an axial stationary screw operating through a linkage mechanism. In the latter case the motor speed may be adjusted while the motor is running; in the former it is necessary to stop the motor and to use tools to change the speed setting.

Lee governors are furnished in sizes from $\frac{3}{4}$ to $4\frac{5}{8}$ in. in diameter and may be applied to motors in sizes from 1 watt to 50 hp. Typical small governor-controlled series motors are shown in Figs. 11·22 and 11·23. In most cases Lee governors will hold the speed regulation of a motor to within $\frac{1}{2}$ per cent for all loads from zero to full load and for line-voltage

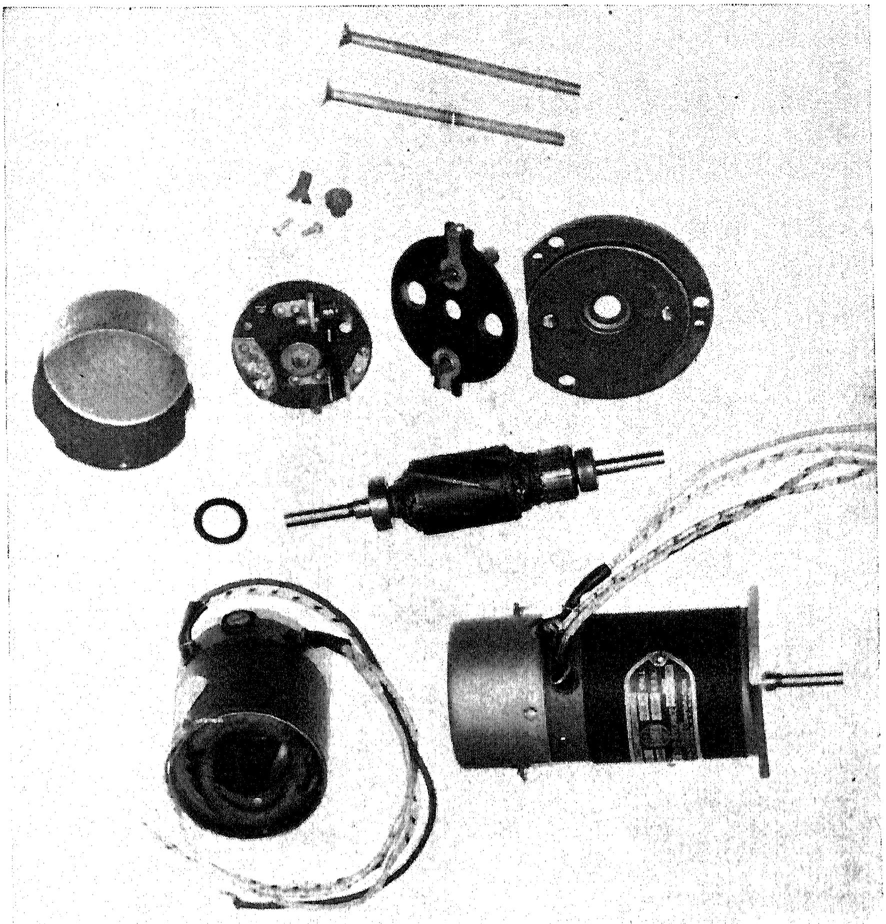


FIG. 11·22.—Delco constant-speed d-c series motor: 27-volt input, $\frac{1}{100}$ hp, 6000 rpm, with Lee centrifugal governor; also made with adjustable-speed governor.

variations of ± 10 to 15 per cent. With special precautions the regulation can be reduced to 0.1 per cent. These figures apply to the fixed-speed types; for the adjustable types the consistency of speed settings for any one governor is very good, but there is a 5 to 10 per cent variation in the speeds for corresponding dial settings of different governors. The makers believe that this variation can be greatly reduced in volume

production if the need arises. Adjustable speed governors would be particularly useful on aided-tracking devices, etc.

Lee governors are adaptable to series, shunt, compound, or PM

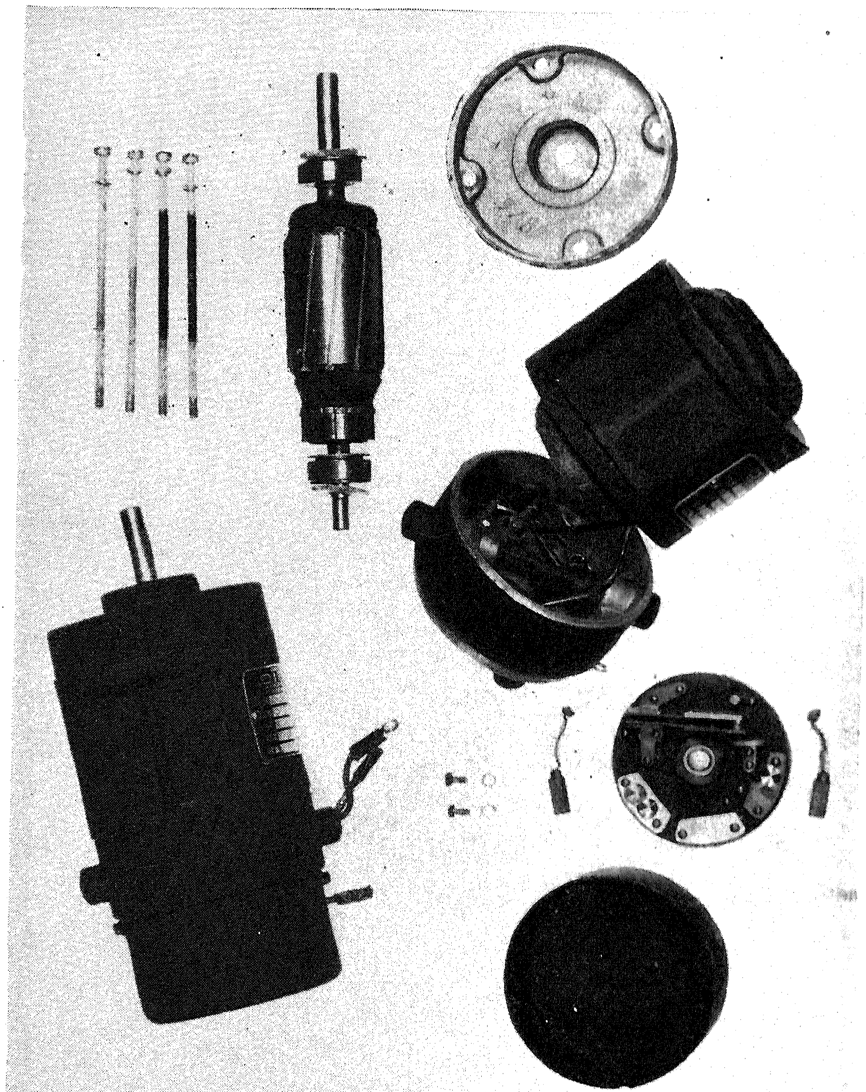


FIG. 11·23.—Diehl constant-speed d-c series motor: 27-volt input, $\frac{1}{30}$ hp, 6000 rpm, with Lee centrifugal governor.

motors. Alternating-current governor motors are available with a 10-to-1 speed range. In cases requiring multiple-speed operation up to three sets of contacts can be mounted on the same governor disk, with

one slip ring added for each contact pair, and two- or three-speed operation can be obtained by switching to the proper set of contacts.

The direction of rotation affects the setting of certain types of governors when operated at speeds below 3000 rpm. The change of setting with reversal of the motor is usually less than $\frac{1}{2}$ per cent.

The thrust button of the adjustable governor is made of linen-base Bakelite. It is lightly lubricated at the factory with graphite, and requires no further attention during the life of the unit. In general the life of a Lee governor is much greater than that of the motor on which it is used.

Not all motors are suited to governor control. It has been found that for best results the controlled motor should have the following characteristics:

1. It should be reasonably efficient.
2. The rotor should have an even number of slots; when an odd number of slots is used the governor action is somewhat erratic and noise and vibration become noticable.
3. The commutator should have not less than 24 bars.
4. The pole faces should be tapered slightly.

A contact-making governor usually must be shunted by a condenser and resistor which are individually adjusted for the particular application. They must usually be mounted externally except in the case of the smallest sizes, for which they may be mounted on the governor disk. The optimum size for the condenser is usually found by trial and error, starting with about 0.5 μf for a small 115-volt motor and increasing the value by 0.25-μf steps until minimum sparking is observed. In some applications it is necessary to add a small resistor in series with the condenser to cut down sparking on making contact. The shunt resistor value for a series motor is found by operating the motor at the highest expected line voltage and lightest load and reducing the resistance across the contacts until the governor loses control. This value is then increased about 10 to 15 per cent to provide a margin of safety.

A shunt motor intended for governor control should be wound to give about 10 per cent less than the desired speed, and then sufficient resistance is added in series with the field to give about 10 per cent excess speed. The governor contacts are shunted across this resistor.

Lee governors can be furnished with tropical treatment. Special governors are also available with Z-nickel springs for operation at very low temperatures.

CHAPTER 12

POWER SUPPLIES

By M. M. Hubbard

12·1. Choice of a Power Supply.—Most electronic equipment ultimately derives the power required for its operation from the commercial power lines, but there are many cases in which commercial power is not available or supplementary or standby power supplies are necessary. This chapter will be devoted largely to a discussion of prime power supplies and the devices necessary to convert their outputs into the forms required by electronic devices, but the last three sections will include discussions of certain types of apparatus which are equally useful no matter what the orginal source of the power.

When commercial power is available it should almost always be used in preference to any other source. There are rare exceptions to this rule, but they are comparatively unimportant. In many cases, however, it is necessary to supplement the commercial power lines with emergency or standby power sources, particularly if continuity of operation is imperative. An example of such a case is a navigational radio beacon in an isolated location where the commercial power lines are subject to failures in times of lightning or sleet storms. Here it would be necessary to provide a standby power plant; if the same beacon were located in a metropolitan area where power failure averaged only a few minutes a year, and particularly if a secondary power line were available, the expense of the additional plant would probably be unjustified.

Even in cases where continuity of operation is of less importance it is often impossible to depend upon commercial power without auxiliary equipment. Common examples of such a situation are the use of apparatus that requires a constant input voltage or frequency on lines with poor voltage regulation and widely varying load conditions. In the first example if the voltage at the load varies slowly enough, a manually adjusted autotransformer may be all that is necessary to maintain constant voltage at the input; in more critical cases more elaborate precautions must be taken. In Sec. 12·13 several types of line-voltage regulators are discussed. Frequency variation is much less often a problem, both because the frequency of most commercial power lines is held within close limits and because most equipment is fairly tolerant to reasonable variations in frequency if the voltage regulation is good. In

extreme cases, however, it might be necessary to install independent power sources even if commercial power were available.

The principal fields of applicability of prime power supplies are, however, portable and mobile equipment, and isolated locations where commercial power is not available. Two cases may be distinguished.

1. In mobile operation there is almost always a source of mechanical power available, and it is usually preferable to connect a suitable generator to the propelling engine and to convert the power furnished by this generator into the desired form. Sections 12·5 and 12·6 discuss generators, with the emphasis largely on aircraft generators, and Secs. 12·7 through 12·11 discuss various forms of converters. Section 12·12 is devoted to the problem of generator-voltage regulation.
2. In mobile equipment that is to be operated when the propelling engine is not running, and in cases such as isolated fixed stations where no such engine exists, it is necessary to supply some other prime power source. This source may be an engine intended only for supplying the electrical power required. Various problems associated with such engines are discussed in Sec. 12·3. Finally, the power may be derived from batteries, which are briefly discussed in Sec. 12·2.

The subject matter of this chapter largely duplicates that of Chap. 14 of Vol. 1 of this series, where power supplies are discussed from the basis of system engineering, with the emphasis upon the selection of the proper power supply for a particular case. Before entering upon a detailed discussion of individual power-supply components it may be in order to present here a brief outline of the fields of application of the different types, following the treatment of Vol. 1.

The problems of fixed locations with commercial power available require no discussion here. The solution, if commercial power is not available, depends primarily upon the magnitude of the load. For loads up to a few watts, especially if the service is intermittent, and if the maximum voltage required does not exceed a few hundred, primary batteries are frequently the most convenient solution. For somewhat greater loads it is usually best to depend upon storage batteries if recharging facilities are available. Recharging (which can usually be done without interruption to service) is usually accomplished by a gasoline-engine–driven generator, although the use of windmill-driven generators and even of water power or small steam engines is often practical.

The power level at which the use of storage batteries becomes undesirable depends largely upon the voltage. A 6-volt battery should not ordinarily be called upon to furnish more than 100 to 200 watts contin-

uously; 24-, 32-, and 110-volt installations are good for powers up to several kilowatts. The limitation often depends more upon the current limitations of the converter than upon those of the battery. It should be noted also that because of its low internal resistance a lead-acid storage battery is about the best generator-voltage regulator and filter that can be obtained, so that even in cases where the power is actually supplied by an engine-driven d-c generator, a battery floated across its output will frequently improve the operation of the system.

Powers greater than those which can be furnished by storage batteries must be derived from engine-driven generators, at which power levels the power is usually generated as a-c and the system design becomes the same as for commercial power, with the added problems of generator voltage and frequency stabilization.

The problems of mobile equipment are essentially the same as those of the locations just discussed, plus the usual restrictions on weight, size, operation at high altitudes, etc., peculiar to the particular service. Electronic equipment in aircraft is usually supplied with power from the 12- or 24-volt d-c system of the airplane, using vibrator power supplies up to about 150 watts, with dynamotors as second choice. For powers in the 150- to 250-watt range, motor-alternators are most useful, with dynamotors again in second place. Motor-alternators are obtainable in ratings up to 2500 watts, but for powers above about 250 watts, direct-engine-driven alternators furnishing 115 volts at 400 cps are usually the best solution. For loads up to 750 watts the generation may be single-phase; above this value, and up to a limit of perhaps 10 kw, 3-phase generation is preferable because of the saving in weight of filters and other components. For the exceptional case demanding more than 10 kw, alternators driven by separate engines are still the only solution.

In land vehicles the situation is much the same as in aircraft, except that the weight restrictions are not so stringent and the space restrictions, if anything, are more stringent. Most automobiles have 6-volt d-c systems; heavy trucks may use 12 volts or even more, and railroad trains ordinarily use 32 volts. Because of the lower voltage, the power that can be drawn from an automobile electrical system is much lower than in the case of an airplane, and engine-generator sets must be used for all powers above a few hundred watts.

In watercraft the situation is again somewhat the same, small boats being comparable with automobiles, PT's and large pleasure craft with aircraft, and ships with land stations. Most older merchant and naval vessels have 120/240-volt d-c systems of adequate capacity for any reasonable load, although the voltage regulation is frequently poor. The newer large craft have 3-phase 60-cps systems, usually with both 115 and 440 volts available. The frequency regulation is usually adequate for

all but the most critical applications, but ship systems are notoriously subject to transient voltage disturbances caused by the operation of heavy gun turrets, plane elevators, etc. In the operation of shipborne radar sets, which are particularly vulnerable to such disturbances, the best solution has been to feed the radar set from an alternator driven by an induction motor, whose speed is relatively independent of voltage.

There are two special cases that do not come under any of the above classifications. One is the ultraportable or man-pack class of equipment, such as paratroop beacons and communication sets, which are usually powered by primary batteries. In cases where the power is too great for batteries the ultraportable gasoline engine sets described in Sec. 12·3 must be used. The other case is that of test equipment, wherever it may be used. Primary batteries are commonly used for test equipment, because the service is intermittent, the power demands small, and the use of batteries in the same case as the rest of the apparatus results in economy of equipment and improved operation. Test equipment also, by its very nature, is more likely to receive adequate attention to battery renewals than are other electronic devices.

PRIME POWER SUPPLIES

12·2. Batteries.—Of the several possible sources of power for operating portable equipment, the Radiation Laboratory has had the least experience with primary batteries since, almost without exception, the power requirements of its systems were much greater than could be supplied from such a source. This section, therefore, will be brief and of a general nature. Both dry batteries and storage batteries have undergone considerable development during the war and much of the information presented here may soon be out of date.

Primary Batteries.—Primary batteries—or, more accurately, "dry" batteries, of the type commonly used for filament and plate power sources in electronic equipment—are particularly suitable for applications requiring powers up to 20 or 30 watts at voltages up to 300 or more. For such applications the principal advantages of primary batteries are portability, silence in operation, instant availability without warmup periods, lack of necessity for filtering, relative cleanliness, and lack of acid spray or fumes. Their principal disadvantage is the small amount of energy that can be obtained before replacement is necessary. Figure 12·1 shows the life of seven typical prewar 45-volt batteries of various sizes, plotted against current drain. In each case, current was drawn for 4 hr per day, and battery life was considered the number of operating hours before output voltage fell to 34 volts per unit. Figure 12·2 shows the same data replotted to show the total energy output in watt-hours, assuming an average voltage of 40 volts for the whole life of the battery.

Division of the ordinates of Fig. 12·2 by the appropriate battery weights causes the curves of the figure to fall more or less on top of each other, giving a figure that is not suited for reproduction, but showing that the total energy output is roughly the same for the various batteries, ranging from about 15 to about 30 w-hr/lb at low outputs, the lower values applying to the smaller units. The currents at which the total output drops to half of its maximum value range from about 20 ma for the smallest unit to about 100 ma for the largest.

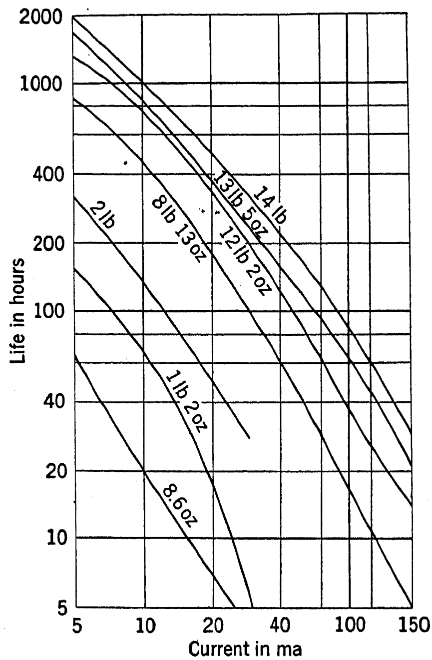


FIG. 12·1.—Battery life vs. current.

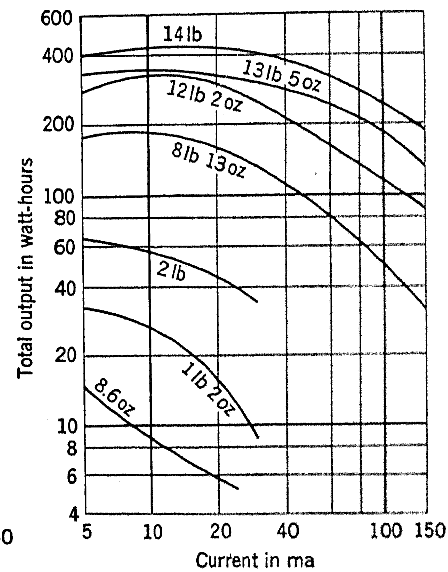


FIG. 12·2.—Total energy output vs. current.

Similar curves can be plotted for batteries of other voltages, and would lead to the same general conclusions. In general, dry batteries will furnish the greatest total energy output at a current that depends upon the size of the cell, but varies from a few milliamperes up to a few hundred. As the current drain is increased the total output falls off, slowly at first and then more rapidly. The total output is also greatly affected by the way in which the current is drawn, intermittent operation allowing much greater output than continuous operation at any but very small currents. It is impossible to give exact figures since the characteristics of a dry battery are greatly affected not only by its design and construction but also by small amounts of certain impurities in the chemicals of which it is made, and by its age, conditions of storage, etc.

Standard Army and Navy dry batteries (and also a few British units) are covered by Joint Army-Navy Specification JAN-B-18, which gives outline drawings and test specifications for 81 different types, including general-purpose and flashlight batteries and a number of special units designed to furnish A, B, and C voltages for particular pieces of equipment. The information included in JAN-B-18 is too voluminous and varied for inclusion here, and reference must be made to it and to the catalogues of various battery manufacturers for specific information.

There is one aspect of the use of dry batteries which should be mentioned here, and that is the possibility of recharging. It is commonly believed that a dry battery cannot be recharged, but this is not necessarily true. Batteries that have not been too much discharged can often be recharged a number of times if the zinc container has not been perforated. Details of the method of recharging have been given by Eubank.[1]

Storage Batteries.—For powers up to several hundred watts, storage batteries are often used where recharging facilities are available. Storage-battery power is used almost universally for electronic equipment intended for use in automobiles, aircraft, and small boats. Edison batteries are used occasionally, but their high initial cost, high internal resistance, and large volume per watt-hour as compared with lead-acid batteries have rendered them practically obsolete except for special applications.

Common storage-battery voltages are 2 volts for small portable or ultraportable equipment, 6 volts for practically all automobiles and most trucks, 12 volts for heavy trucks and many civilian aircraft, 24 to 28 volts for military airplanes, tanks, etc., and either 32 or 110 volts for farm-lighting equipment and small boats. Most Radiation Laboratory equipment intended for storage-battery operation was designed for a 28-volt supply.

12·3. Engines.—For power requirements in excess of those which can be supplied by batteries, or in other cases in which the use of battery power is inadmissible, it becomes necessary to use engine-driven generators. Engine-driven generators may be divided into three categories:

1. Large ground systems.
2. Portable ground systems.
3. Ultraportable systems.

Large Ground Systems.—Large ground systems of the 10-kw class and larger have in general been satisfactory and have not received the criticism which has been prevalent with the smaller units. This is principally because the larger systems were intended for permanent or semipermanent installation and were therefore designed with little or no

[1] R. N. Eubank, "Restoring Dry Cells," *QST* **28** No. 6, 11–15, (June 1944).

attempt at weight reduction. Conservative design has produced units which, although cumbersome, have been dependable and conservatively rated, and which usually have given more satisfactory service with less maintenance than the smaller units. In the higher-power class, also, there is usually the choice between Diesel and gasoline engines. The Diesel is heavier and less subject to numerous minor ailments than the gasoline engine, but when trouble does occur with a Diesel it is usually of a more serious nature. Diesel fuel is less easy to obtain than gasoline, although it is becoming more readily available with the increasing use of small Diesel units.

Portable Ground Systems.—Undoubtedly the most widely used class of power supply has been the portable type in the 1- to 5-kw range. Since this class is at the limit of the man-pack–size range, a great deal of emphasis has been placed on weight reduction, sometimes at the expense of other necessary qualities. In the past most of these units have been air-cooled, but the trend at present is towards water cooling since it permits more uniform operation. Much work has been done on packaging for transporting the larger portable systems that weigh about 500 lbs. In order to reduce the weight per package some effort has been made to split the system into two components. This has been done in either of two ways: by using a direct-connected unit with a quick-disconnect coupling, or by using a belt-connected unit. The former method has been unsuccessful because of the difficulty of realignment in the field and the requirement of a heavy rigid base to maintain this alignment. (Parenthetically, it might be remarked that it does not seem out of the question to avoid both difficulties by the use of properly designed mating flanges on the engine and generator units.) The use of a belt connection offers two principal advantages: it obviates the necessity of accurate alignment, and it permits operation of the engine at a different shaft speed from that of the generator. This allows the use of a high-speed generator of small size and high performance with an engine operating at its most economical speed. The principal disadvantage is the increase in weight entailed in making the engine and generator structurally separate units. This disadvantage, plus the possibility of receiving two engines or two generators instead of one of each when the units are packaged separately, has led the Services to favor the single-unit systems.

Portable power supplies in the 5-kw class have employed many makes and types of engines but perhaps the most widely used have been the Hercules Models ZXA and ZXB. These engines have an excellent reputation for performance and reliability and at the same time are easy to maintain.

Ultraportable Systems.—The field of ultraportable power supplies was largely unexplored before the war, but the design of very light equipment

for paratroop operations, etc., produced the need for a very lightweight unit with an output of about 150 watts. The maximum weight of such a unit was placed at about 15 lb. Several companies have attempted to supply such units, and so far the most successful have been the Jacobsen Manufacturing Company of Racine, Wis., and the Judson Manufacturing Company of Philadelphia.

The Jacobsen Manufacturing Company has produced a unit with a total weight of $12\frac{3}{4}$ lb including fuel tank and carrying frame. It has a two-cycle single-cylinder engine driving a direct-connected generator with an output of 125 watts at 400 cps. Ignition is obtained from a magneto, the housing of which serves as a blower wheel for the air blast. Engine speed is controlled by an air-vane governor. This unit has been satisfactory but must be shut down for about 10 min every 20 or 30 hr of operation to permit cleaning of the exhaust ports.

The Judson Manufacturing Company has produced several units in this power range. One of these is a single-cylinder $1\frac{3}{16}$ by $\frac{15}{16}$ in. two-cycle air-cooled engine belt-connected to a 150-watt generator. This unit is also controlled by an air-vane governor and operates at a speed of 5600 to 6000 rpm. It uses a fuel consisting of 60 parts of gasoline to one part of oil and does not foul as rapidly as the Jacobsen engine; cleaning of the exhaust ports can be done while the engine is in operation since the ports are removable. Including carrying frame and fuel tank this unit weighs approximately 15 lbs.

Another model developed by the same company utilizes the generator as the source of the ignition, and weighs only $8\frac{3}{4}$ lb for a 150-watt output. The company has also developed a magneto which weighs well under 1 lb, as compared to 4 lb for a standard magneto.

Some work has also been done on the design and development of other types of prime movers, such as steam engines and turbines, air motors, gas turbines, etc. Although both air motors (windmills) and waterwheels may be used occasionally for charging batteries, to date there appears to be nothing that competes seriously with the gasoline engine in the small-power field.

12·4. Selection of an Engine-driven Generator Set.—In selecting engine-generator sets it is advisable to give serious consideration to both engine and generator specifications. The practice of ordering such equipment on rating alone is certain to result in disappointment and inadequate performance if the unit is to supply power to equipment whose operation is affected by variations in supply voltage, frequency, or waveform. It must be remembered that most commercial engine-generator sets are intended for use with lights, electrical appliances, motor-driven tools, etc., whose performance requirements are not critical. The use of such sets to supply power to radar systems has led to disappointment in

the past. It should be understood at the start that an ideal machine can never be obtained, and that compromises are always necessary. If the dangers are known and understood, however, they can be minimized by suitable precautions in the design of both the generator set and the system.

As a general guide to available equipment and manufacturers the Signal Corps booklet TM-11-223 on power supplies lists a large number of sets. A word of caution is necessary in the use of this guide, since it appears that sufficient attention has not been given to the electrical characteristics of these sets in all cases and as a result it is necessary to consider most of the points outlined in this section even in choosing from accepted Signal Corps machines. Reference may also be made to the American Standards Association publication C50-1943, *Rotating Electrical Machinery.* While the selection of a suitable engine and that of the generator which it is to drive cannot be made independently of each other, the present section will be devoted primarily to problems associated with the engine, deferring questions regarding the generator until the next section.

In selecting the engine for an engine-generator set it is necessary first to determine the conditions under which the set will have to operate. Once these conditions are determined, consideration should be given to the following factors.

1. Type of duty
2. Power required
3. Type of fuel
4. Two- or four-cycle engine
5. Type of cooling
6. Type of ignition
7. Speed of operation
8. Controls
9. Maintenance

Type of Duty.—Nearly all the power requirements for service equipment require an engine-generator capable of continuous operation with a relatively small percentage of shutdown time. Prior to the outbreak of the war this requirement could only be filled by the use of a very slow speed and hence a very heavy unit. Since these heavy units would be satisfactory only in permanent installations, considerable work was done to decrease the weight and increase the speed and hence provide a more portable unit. It was desirable to do this without a sacrifice in reliability. Since this was found to be nearly impossible the Signal Corps finally established a program whereby two sizes of engine would be built for every generator rating. This permitted one lightweight unit and one

heavy-duty unit for each rating. In order to minimize the number of different engines, one engine is designed for two speed ranges; thus a lightweight engine becomes a heavy-duty engine of the next smaller power range. Except in cases where weight is the primary consideration, a heavy-duty unit is desirable, because of its greater reliability and increased life. The advantage of increased reliability should outweigh the weight reduction considerations for all ratings except those which are of the back-pack class.

Power Required.—Normally the selection of an engine for a certain generator is done by the manufacturer of the unit and need not be considered. Should this not be the case, a minimum horsepower of 1.7 times the output of the generator in kilowatts is advisable. This factor of 1.7 is often increased to as much as 3 for a more conservative design, depending on the type of operation to which the unit will be subjected. A figure somewhat nearer 3 would be recommended for a unit that is to be used for continuous service. When endeavoring to select an engine for a generator that must be suitable for fully automatic service—that is, capable of starting under full load—this factor must be still further increased to approximately 6. An example of a unit of this type is that used on all engine-driven welding equipment. Here striking of the arc actuates the throttle by means of a solenoid and immediately throws approximately full load on the engine. When the arc is broken the unit idles in order to save fuel.

Type of Fuel.—At the outset of the war it was felt by the Armed Services that they could use existing industrial units, possibly altered to provide more convenient handling, and place them directly into field applications. These units, employed principally as rural lighting plants, were using butane, natural gas, and "white" gas as a fuel and few difficulties were encountered. With the use of the so-called "all-purpose fuel," an 80-octane gasoline containing tetraethyl lead, numerous failures were encountered ranging from burned valves to fouled plugs. This trouble was finally isolated and attributed to the tetraethyl lead. The substitution of stellite valves, aircraft-type spark plugs, etc., has reduced these failures to a minimum. Considerable work is still being done on this problem, especially with the use of 100-octane aviation gas. When it is proposed that a unit must run on higher octane fuels (80-octane or over) the use of stellite valves, aircraft spark plugs, etc., should be considered a "must," but for operation on fuels such as butane, natural gas, etc., the standard type of industrial equipment is adequate. The use of the higher octane fuels should be avoided whenever possible in order to decrease the maintenance necessary.

Two- or Four-cycle Engine.—There is considerable controversy as to whether a two- or a four-cycle engine is preferable. To date, the four-

cycle engine has been considered preferable partially because more research and development have been done on it, and partially because of a general prejudice against two-cycle units, resulting from their poor showing. During the past few years considerable work has been done on the design, balancing, silencing, etc., of two-cycle engines and they should become increasingly popular. The problem of maintenance becomes simplified because there are fewer things that can go wrong; that is, there is no oil to change, no external parts to lubricate, no periodic tappet adjustments, etc. The principal disadvantage of a two-cycle engine is that it requires the mixing of oil and gasoline for fuel. This is probably the cause of more failures than any other single factor. If this mixing is forgotten or performed incorrectly, a failure is inevitable, since this is the only means of lubrication. Should there be some way of decreasing this danger, such as by the use of "ready-mixed" fuel, the two-cycle engine would be preferable to the four-cycle engine because of its simplicity of construction and maintenance, its lighter weight, etc.

Type of Cooling.—There are three principal methods used for the cooling of internal-combustion engines. Perhaps the simplest cooling system is the air type in which a blast of air from a fan or blower mounted on the engine is directed across the cylinder. The cylinder is provided with numerous fins, either machined or cast integrally, to increase the heat-transfer coefficients. Advances in casting techniques have greatly improved the results obtainable from cast fins by making possible a greater number of fins per unit of length of cylinder and by improving the surface condition of the fins themselves. This method of cooling, although probably the simplest, is also the most subject to other factors such as direction and velocity of wind, ambient temperature, etc. These factors all affect the engine temperature and hence the operation.

Perhaps the most common type of cooling to date is the so-called "radiator" type in which water from the engine jacket is cooled in a heat exchanger (radiator) by means of an axial-flow fan. This type of cooling utilizes two different methods of fluid transfer: the use of a water-circulating pump and the thermosiphon system. Radiator cooling, while still the most popular, does not prevent changes in engine temperature and hence in performance. In other words, it is still affected by the ambient conditions.

The system that shows the greatest promise both from the standpoint of weight and performance is the constant-temperature or vapor-phase system. This system, developed largely by the Fort Monmouth Ground Signal Agency, utilizes the heat of vaporization of water and cools with a centrifugal fan through a radiator condenser. Since the system is of the thermosiphon type, the use of a circulating pump is eliminated, and hence increased horsepower output becomes available. The usual dif-

ficulties of fouling at light loads are eliminated since this type of system automatically controls the engine temperature at all conditions of load and ambient temperature. Since less liquid is used in this type of system than in the radiator type, considerable weight is saved. The system as now developed operates at atmospheric pressure and requires no pressure valve.

Type of Ignition.—The two types of ignition systems in use today are the battery type and the magneto. The former utilizes a battery, a high-voltage coil, a distributor, and a breaker and is operative only when the battery is charged. This system is used primarily on self-starting units that require a battery for starting. The principal disadvantage of this system is that if the battery fails there is no way of starting until sufficient charge can be stored in the battery.

The magneto consists of a generator, a coil, a breaker, and a distributor mounted as a unit. This system requires no outside excitation and hence is greatly preferred. In addition most magnetos can be obtained with a so-called "impulse coupling." This coupling is especially useful when endeavoring to start a unit by hand. When this is done, the coupling gives a slight impulse to the magneto armature at the proper time and hence gives a better spark.

In order to decrease weight still further, development has been under way for some time on the problem of taking the ignition directly from the generator. This type of ignition system shows great promise but can be used only with permanent-magnet generators. It is especially beneficial with ultraportable units where the weight of the magneto is often as great as that of the generator itself.

The problem of shielding the ignition system is one that comes up frequently, especially in connection with radio equipment. The only effective type of shielding is that consisting of a flexible metal hose with the necessary end fittings to connect to the magneto (or generator) and shielded spark plugs. The subject of proper shielding is complex and cannot be treated here.

Speed of Operation.—The speed of operation of an engine has been mentioned previously in this section in relation to lightweight and heavy-duty machines. Control of the speed of the engine is accomplished by means of a governor of the mechanical or electrical type. The mechanical-type governor is usually a pair of flyballs driven at high speed from a power take-off on the engine. This type of governor consists of many moving parts and hence is subject to the usual maintenance problems.

A recently developed governing mechanism of the electrical type utilizes a solenoid controlled by the output voltage of the generator. The solenoid design has been perfected to provide stability under all conditions of operation and can be used to provide a rising speed charac-

teristic. This characteristic is important in order to obtain combined voltage and frequency regulation within the normal limits for permanent-magnet alternators whose inherent voltage regulation is poor. In this way the necessity of a voltage regulator is eliminated.

Controls.—The use of automatic controls such as automatic chokes, remote controls, automatic shutoffs for high water temperature, low oil pressure, etc., should be avoided whenever possible. These controls serve only as possible sources of trouble and accomplish nothing that a slight amount of care and thought will not accomplish as well. The indicating instruments should likewise be limited to those actually necessary, such as a voltmeter, frequency meter, hour meter, engine-water thermometer, oil-pressure gauge, etc.

Maintenance.—The problem of proper maintenance of power supplies is one that cannot be overemphasized. The same maintenance technique and schedule is often applied to an engine-generator that is commonly used on automobiles even though an automobile is usually operated as an intermittent-duty machine and hence does not require the same maintenance. It is desirable that a definite daily maintenance procedure be established in order to make a frequent check of the operation. In this way failures are more likely to be foreseen before they occur, in time to apply corrective maintenance. The use of trained personnel in the maintenance of power units is essential if the best performance is expected. Much emphasis has been placed on the training of personnel to operate the power-using equipment but very little training has been given to personnel on operating and maintaining the power equipment. A better balance of this training should be achieved.

It should also be recognized that since power is essential to the operation of the power-using equipment, a sufficient number of units must be provided to permit continuous operation while individual units are shut down for preventive maintenance.

GENERATORS

12·5. Generator Specifications.—In ordering generators for specific applications the following characteristics should be specified on the order or request for quotation.

1. Rating
2. Type of winding (for d-c generators only)
3. Type of excitation
4. Type of voltage control
5. Enclosure
6. Bearings and lubrication
7. Special considerations

D-c Generator Ratings.—The rating of a d-c generator includes the following: kilowatts, voltage, current, speed, duty, and temperature rise. Of these, the last two require some explanation.

Duty is usually classified as continuous, short-time, or intermittent. Most applications call for continuous duty, and other duty classifications can be applied only if the maximum continuous-operating period of the generator is 1 hr, after which it will remain at rest until cool.

Temperature rise pertains to the rise in temperature of the windings over the ambient temperature after the machine has reached operating temperature at full load. Allowable temperature rise is determined by the type of insulation used and the maximum ambient temperature to be encountered. Standard values and further explanation of these points are given in the American Standards Association publication C50-1943.

A-c Generator Ratings.—The rating of an a-c generator includes the following: kilovolt-amperes, kilowatts, voltage, current, power factor, phase, speed, duty, and temperature rise.

Type of Winding (D-c Generators).—D-c generators may be series-wound (having all field windings in series with the output), shunt-wound (having all field windings connected across the output terminals), or compound-wound (having both series- and shunt-connected fields). They may be wound either with or without interpoles.

Series-wound generators are seldom used, except as exciters, since they produce only residual voltage at no load and hence are generally unsuitable for constant-voltage applications. Furthermore, the control of field current involves handling of much greater currents than in the case of shunt-wound machines.

Shunt-wound generators are commonly used where automatic control of the output voltage is provided, or where manual control over a wide range of voltages is desired. Shunt-wound generators have inherently poor voltage-regulation characteristics, and hence are not suitable for constant-voltage use without some form of automatic field control.

Compound-wound generators are useful where a roughly constant voltage is desired over the entire load range, and where it is desirable to eliminate voltage regulators. Factors to be considered in the use of compound-wound generators are—

1. Speed of driver. Compound generators without voltage regulators produce voltage variations in proportion to the speed variations of the driver. In the case of an engine, unless the governor is very stable and consistent, undesirable voltage variations will occur. Often the governor performance on small engines deteriorates appreciably after usage.
2. Ambient and winding temperatures. Compound generators

without regulators will produce output-voltage variations with changing ambient and winding temperatures, thereby requiring continuous readjustment of the voltage during the warmup period. It is possible to counteract this effect by the use of negative-temperature-coefficient materials, and if this is desired, it should be specified in the design, rather than added later.

3. Use over a wide range of voltages. A compound generator, in general, will have a flat voltage-load curve only for one voltage. If it is operated above that point the voltage will droop under load. If it is operated below that point, the voltage will rise under load. This is true only under saturated conditions, but for the sake of stability it is necessary to operate there. Consequently, the use of a flat-compounded machine over a wide range of voltages will produce unsatisfactory regulation, and control will be difficult.

In general, for constant voltage applications, the most reliable operation can be obtained by the use of a shunt-wound d-c generator plus a suitable voltage regulator, especially where a gasoline engine is the prime mover.

The use of interpoles falls in the realm of design rather than of application, and is normally left to the discretion of the manufacturer.

Type of Excitation (D-c Generators).—The type of excitation used on a generator has considerable bearing on its control problems and characteristics, and should therefore be considered in selecting equipment.

Most d-c generators smaller than about 15 kw—and many larger ones—are self-excited, using the types of field windings described above. Self-excitation eliminates the need of an extra exciter generator or other power supply for field excitation. It is a convenient and economical form of excitation when the field current is small enough to fit the desired type of control, and when the generator will not be operated below saturation, which would lead to instability.

When the magnitude of the main generator field current becomes too large for the type of control desired, or when the desired operating range of the generator extends below saturation, the use of an exciter generator is advisable. By this method the control may be transferred from the main generator field to the exciter field, reducing the control current by a factor of 10 or more. Exciter generators are usually attached to the main generator. It should be noted that exciters themselves are open to the criticism voiced above regarding instability below the saturation point. Since exciters are usually operated over a very wide range, this is an important consideration. Considerable ingenuity is required in the design of a stable exciter, and many regulating difficulties can originate in poorly designed exciters. However, it is possible

to design stable exciters by the use of methods not advisable in the main generator for reasons of economy, efficiency, and operating characteristics. It should also be noted that the use of an exciter adds another time lag to the response characteristic of the generator.

Type of Excitation (A-c Generators).—A-c generators are said to be self-excited when a d-c exciter winding is wound on the same rotor core as the main a-c winding, and both have a common field. Thus, the exciter generates its own field, which also serves as field for the main generator. This arrangement is usually used on small a-c generators, and is a compact and inexpensive type of construction. It lends itself to the same type of control as do separate exciters but with more inherent speed of response.

In the case of larger a-c generators, independent exciter generators are usually attached to the main generator. In general, the above discussion of d-c generators with attached exciters applies also to a-c generators with attached exciters.

Type of Voltage Control.—In regard to the general problem of selecting a voltage regulator for a specific application, a few comments are relevant (see also Sec. 12·7). The voltage regulator must be matched to the performance characteristics of the exciter and main generator which it controls. A regulator designed to control a specific generator and exciter may be useless when applied to another generator and exciter of identical power rating but different characteristics. If it is necessary to order the voltage regulator from a different manufacturer than that of the generator, the following data should be supplied to the manufacturer of the regulator:

1. The complete name-plate rating of generator and exciter.
2. The exciter saturation curve, showing both increasing and decreasing field current portions, with the alternator field as load on the exciter output and a record of the speed at which data were taken.
3. The load curves (field current vs. kilowatt load at rated voltage) of the main generator with a resistive load and (on a-c generators) at rated power factor (usually 80 per cent lagging).
4. The cold resistances of the exciter field and the main generator field as well as the temperature at which the resistances were measured.
5. The actual temperature rises (by the resistance method) of the exciter field and main generator field under maximum-rated-load conditions.
6. The ambient temperature range over which the generator is required to operate.

7. The speed-vs.-load curve of the engine-generator unit.
8. Any unusual operating conditions or requirements that may affect regulator design.

It must also be remembered that in many cases the choice of a regulator may be a primary consideration (as in the case where electronic control is required), and may, therefore, dictate certain requirements to the generator and exciter manufacturer. For instance, it may be desirable to keep the exciter field current below 400 ma in order to use a certain type of electronic control. Such a requirement will definitely influence the choice of generator and exciter, and should therefore be considered in the early stages of the design.

Enclosures.—The type of enclosure required on the generator depends on the intended operating conditions, and should be specified at the time of ordering. The most common type of enclosure in current usage is the semienclosed, or drip-proof type. Other enclosures are: the open, the totally enclosed, the totally enclosed fan-cooled, the explosion-proof, the splash-proof, and others. The Bureau of Ships has formulated a complete set of definitions for enclosures and the conditions under which each should be used, which is helpful as a guide in selecting the appropriate type.

Bearings and Lubrication.—Generator bearings may be of either the sleeve or the ball type. The use of sleeve bearings on Service equipment is not recommended because oil leakage is unavoidable when the equipment must be moved frequently. Furthermore, the danger of a bearing burnout is greater for sleeve than for ball bearings if periodic lubrication is neglected. The use of double-shielded ball bearings is not recommended because of maintenance difficulties encountered. The experience of the Radiation Laboratory has led to the conclusion that a 1000-hr life is all that can be expected from double-shielded ball bearings under normal conditions of operation. After this time the lubricant becomes burned to such a degree that its effectiveness is impaired. Further use results in overheating and finally in binding. Double-shielded bearings must be replaced every 1000 hr, which requires dismantling the generator, removing old bearings, inserting new ones, reassembling the generator, and sometimes realigning it with the engine. Considerable damage may be done in this process, and the realignment is critical. Furthermore, the loss of time during this servicing operation may be serious. For these reasons it appears that the most satisfactory type of bearing and lubricating system consists of the use of open ball bearings in adequate grease reservoirs, fitted with a means of introducing new grease and exhausting the old, and supplied with grease retainers to prevent the flow of grease into the generator frame.

Special Considerations.—There are a number of special considerations which influence the design of the generator. They are listed below as a reference check list for consideration in ordering equipment.

1. Size limitations
2. Weight limitations
3. Allowable limits of voltage regulation
4. Allowable limits of frequency variation
5. Waveform requirements of a-c generators
6. Requirements for operation in parallel with other generators
7. Noise-level restrictions (both mechanical and electrical)
8. Vibration and shock conditions
9. Ambient conditions likely to be encountered
   a. Ambient temperature range
   b. Ambient humidity range
   c. Altitude range
   d. Exposure to explosive or combustible atmospheres, dust, sand, lint, salt air, corrosive chemicals, fungus

12·6. Aircraft-engine Generators.—The large numbers of generators required for combat aircraft and the comparatively few sizes and types needed have permitted such units to be standardized to an extent that has been impossible with generators for other applications. If is worth while to describe aircraft-engine–driven generators at some length both because of their own importance and because they represent present generator design practice.

The present standard electrical system used in U. S. military airplanes is nominally 27.5 volts d-c. This is supplied by generators mounted on each engine of the airplane and connected in parallel. Each generator is geared to the crankshaft of its engine, its speed varying with the engine speed. A voltage regulator is connected to each generator to maintain the voltage at 27.5 ± 2.5 volts.

The generator jack shaft is geared up from the crankshaft by a ratio of 1.75 in Curtiss-Wright engines and 3.15 in Pratt and Whitney engines. Over the normal range of engine revolutions per minute from minimum cruising speed to take-off speed, this gives a jack-shaft speed range of 2000 to 4000 rpm and 4000 to 8000 rpm for the two engines. It is necessary, therefore, to build two series of generators to operate in the two speed ranges. For each series, generators are built in a number of current ratings, of which the most commonly used are the 100-, 200-, and 300-amp sizes, designated by the letters O, P, and R respectively. The six most common Army generators are shown in Table 12·1.

Generators have also been built with 25- and 50-amp outputs, but these sizes are no longer in general use. Generators rated at 500 amp

have been built experimentally but it is doubtful if they will be used, since the trend is toward higher voltages when such large power ratings are required.

Occasionally it becomes necessary to drive a high-speed generator from a low-speed jack shaft. Planetary "sandwich" gear boxes have been developed which can be inserted between the generator and the mounting

TABLE 12·1.—SIX ARMY GENERATORS

Designation	Speed, rpm	Current, amp
O-1	2000–4000	100
P-1	2000–4000	200
R-2	2000–4000	300
O-2	4000–8000	100
P-2	4000–8000	200
R-1	4000–8000	300

Note that the speed designations of the 300-amp generators are reversed; this causes much confusion.

pad on the engine and which give a 2 to 1 increase in generator speed. Experimental governor-controlled variable-speed transmissions have also been built for installation in the same position, but to date have not been particularly successful.

The space available for the generator on a standard engine is limited to a maximum over-all length of about 14 in. and a maximum diameter of $6\frac{1}{2}$ in. The maximum permissible weight is approximately 55 lb. In order to get a generator with a power rating of as much as 9 kw into this space, it must be blast-cooled to dissipate its losses.

Brush wear became a problem as the airplane ceiling was raised above 20,000 ft. At that altitude, excessive dusting and wear take place because there is insufficient oxygen and water vapor to provide a lubricating film of copper oxide on the commutator as well as insufficient air for adequate cooling. Extensive investigation and experimentation on special brush materials and treatments were begun, and today this is no longer a serious problem although brush life at high altitude is still considerably less than at sea level. During the period when brushes were giving so much trouble, other means of power generation were tried. One of these was a 3-phase a-c generator, rated approximately 30 volts, which used a blast-cooled selenium rectifier. For this generator, slip rings were used instead of commutators, and the current density through the brushes was much less than in the case of a d-c generator. When satisfactory high-altitude brushes were developed, however, this scheme was dropped because it had the disadvantage of greater weight and com-

plexity. It has since been revived with generation at 120 volts instead of 30 volts to supply a high-voltage d-c airplane distribution system.

In order to obtain the high-voltage direct current required for radar sets, the airplane low-voltage direct current is converted to 115 volts a-c at 400 or 800 cps by means of a motor-generator or inverter; this voltage is stepped up and rectified. This will be discussed later, but it is mentioned at this point in order to introduce the discussion of dual-voltage

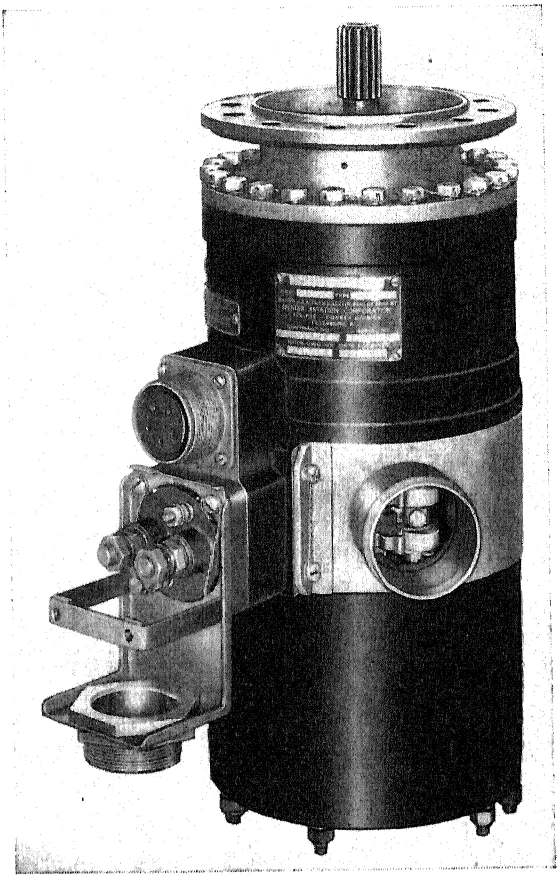


FIG. 12·3.—Eclipse NEA-7 dual-voltage generator.

generators. In the case of small single-engined airplanes that carry a considerable amount of electronic equipment, it is often possible to reduce power losses and weight by having the a-c generator mounted directly on the engine. Since the d-c load of these airplanes is not large, it is possible to place both windings in the same generator frame. The two largest generators of this type are the NEA-6, rated 28.5 volts, 75 amps d-c, and 115 volts, 3.4 kva single phase, 800 to 1600 cps a-c; and the NEA-7,

rated 30 volts, 125 amps d-c and 120 volts, 2.5 kva single phase, 800 to 1600 cps (see Fig. 12·3). Because of the variable frequency, all motors must be d-c. If a small amount of constant-frequency power is required an inverter can be installed.

In one special system in a single-engined carrier-based airplane both d-c and a-c requirements were large, and separate d-c and a-c generators were driven from the engine through a gear box (see Fig. 12·4). The ratings of the generators were: 30 volts, 300 amps d-c and 120/208 volts, 10 kva, 3-phase, 600 to 800 cps a-c. The constant-frequency requirement was approximately 140 watts, which was furnished by a 250-va 600-cps inverter.

This system is now being installed in a four-motored airplane and initially the 10-kva 3-phase alternator will be driven by a suitable d-c

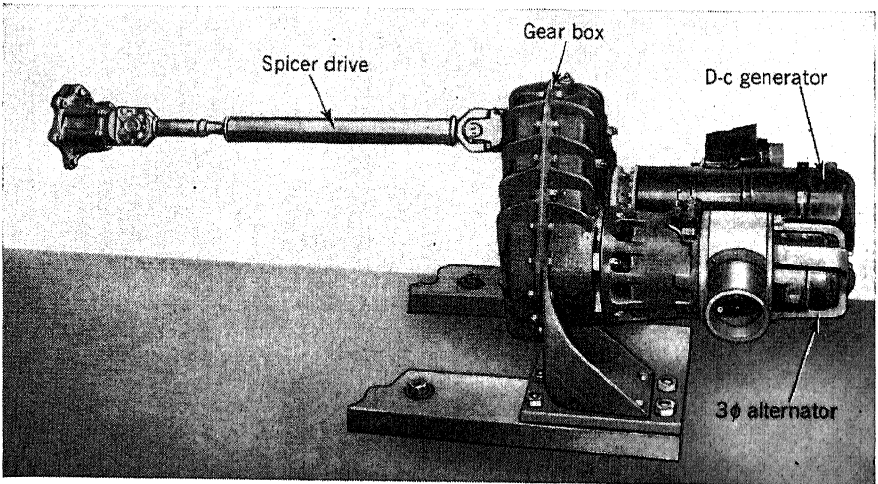


FIG. 12·4.—General Electric Company dual-output gear box and generators for 3-phase a-c radar power and aircraft d-c supply.

motor. For future installations a gear box similar to that used in the small airplane has been designed, and it is expected that it will be placed in each of the two outboard-engine nacelles giving a total power installation of four 300-amp d-c generators and two 10 kva alternators, which will give maximum reliability, flexibility, and reserve capacity with minimum power losses.

With the increase in the electrical load in airplanes, particularly military airplanes, serious consideration has been given to the possiblility of higher-voltage generation, either d-c or a-c. Because of its greater flexibility the present trend is toward alternating current with 3-phase four-wire, 120/208-volt. In this case no d-c generation is contemplated and the alternating current must, therefore, be of constant frequency in

order to permit parallel operation and to carry motor loads. This has been accomplished on an experimental basis by means of a hydraulic drive that consists of a hydraulic pump with variable stroke driving a hydraulic motor. The stroke of the pump is controlled by a governor that operates to maintain a constant output-shaft speed regardless of engine speed. The alternator is driven by the output shaft. A drooping characteristic is introduced in the speed-load curve by means of current transformers placed in the main leads of each alternator. This arrangement insures proper division of load when two or more alternators are operated in parallel. Individual voltage regulators connected to each alternator are adjusted to maintain constant voltage and to divide the reactive kilovolt-amperes among alternators operating in parallel. At the present time the generators which have been built for this experimental setup are rated 40-kva, 3-phase, 120/208-volt, 400-cps, 6000-rpm. The alternators are somewhat larger than the maximum dimensions given earlier, and the nacelle and mountings must be designed to support the alternator as well as the hydraulic drive. The weight of the generator is approximately 80 lb, and of the hydraulic drive, 90 lb.

CONVERTERS

12·7. Motor-generators and Dynamotors.—There are many cases in which the electrical power available is adequate in magnitude but of the wrong voltage. When the supply is a-c, which is the usual case in all except mobile or military installations, the customary transformer-rectifier-filter arrangement will serve to supply almost any electronic device, but when only d-c supply is available, some type of converter must be used. Depending upon circumstances, this converter may be a motor-generator with either d-c or a-c output, a dynamotor with d-c output, or an inverter or vibrator with a-c output.

Little need be said on the subject of motor-generator sets in addition to the discussion in Sec. 12·6. The basic factors are the same whether the generator obtains mechanical power from a gasoline engine or from a d-c motor. The special factors pertaining to the motor are discussed in Chap. 11 and (where speed regulation is concerned) in Sec. 12·8. It should be noted that d-c to d-c motor-generator sets are seldom used for military or mobile equipment because of their great weight and size compared to dynamotors. Their principal advantage is the possibility of individual regulation of each output.

Dynamotors find their principal application to loads requiring moderate amounts of power at voltages up to 1000 or 1200 volts. In this range their weights are often less and their efficiencies greater than those of an inverter plus a transformer and rectifier. A dynamotor is essentially a rotating d-c transformer; it has conventional d-c shunt- and

series-field windings on the stator, and one or more armature windings on the rotor. The primary winding is excited from the input voltage through brushes and a commutator. In the case of a single winding, this winding is tapped to give the required secondary voltage. Separate secondary windings have a fixed turns ratio to the primary winding and they determine the output voltage or voltages. The secondary windings are brought out through commutators to give the required d-c voltages. Dynamotors have been built with voltages as high as 2000 but this is inadvisable because of difficulties with commutation and insulation. Dual- and triple-output dynamotors are common, and several machines

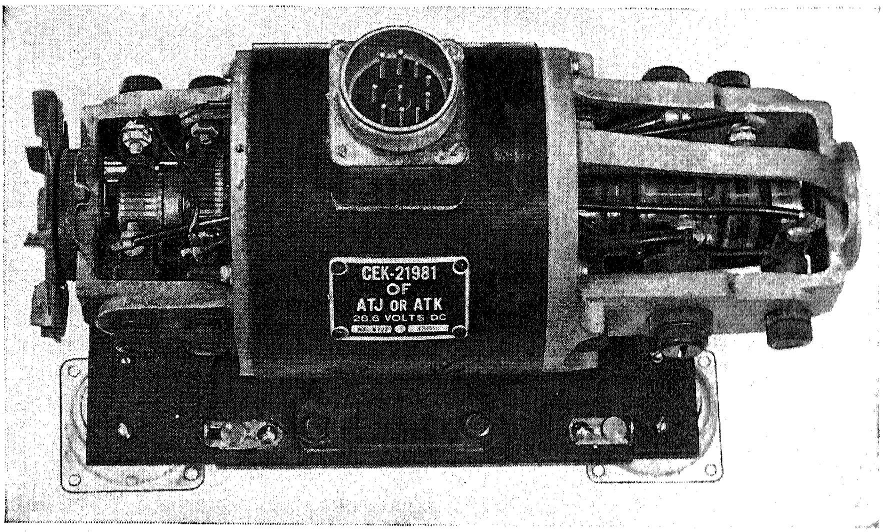


FIG. 12·5.—Eicor, Inc., aircraft dynamotor.

having four outputs (Fig. 12·5) have been built, but it is impractical to go beyond this because of the large number of windings and commutators involved.

Dynamotors for military aircraft are built for an input voltage of 27.5. For automobiles, commercial airplanes, and miscellaneous uses, dynamotors are built for input voltages of 6, 12, 32, and 110. The outputs may vary from 14 volts or less to over 1200 volts, from 5 amp to 30 ma, and in any combination of two, three, or four at a time. Weights vary from 5 lb for a total output of 20 watts, to 26 lb for an output of 400 watts. Efficiencies range from 40 to 60 per cent.

One disadvantage of the dynamotor is its inherently poor regulation. In addition to the regulation of the dynamotor itself there is the variation in input voltage, which may be as much as 10 per cent. To overcome the second difficulty, the dynamotor can be designed for an input voltage

of 19 or 20, assuming a nominal input voltage of 27.5 and a variable resistor in series with the line. This resistor usually takes the form of a carbon-pile voltage regulator having the carbon pile in series with the line and the operating coil across the line just ahead of the dynamotor. With an input variation of 25 to 29 volts and at constant load, the regulation of the output voltage can be held within a range of 5 to 10 per cent; but, of course, with changing load this will be materially increased.

A recent development to improve dynamotor regulation has been the construction in the dynamotor itself of a booster armature winding and regulating field. A three-voltage dynamotor is shown in the photograph of Fig. 12·6, and the circuit of a dual-voltage machine is shown schematically in Fig. 12·7. In any multioutput dynamotor only one voltage can be regulated, but, except in the case of very unevenly loaded circuits, the

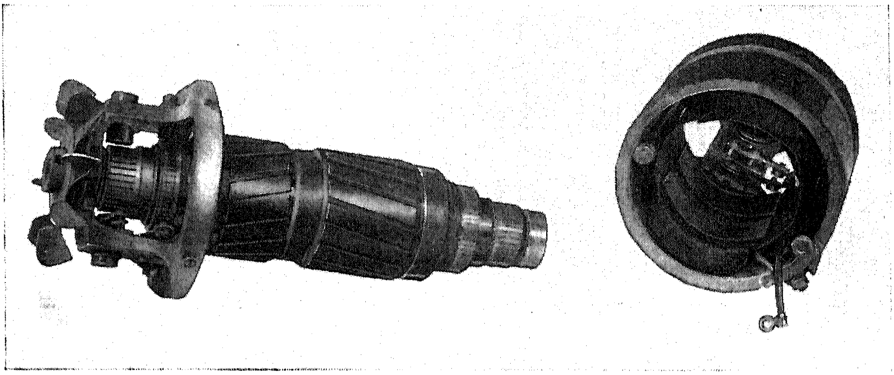


FIG. 12·6.—Bendix dynamotor.

unregulated voltages will closely follow the regulated voltage. There are several ways in which the regulating feature may be handled.

1. All output circuits may have windings on the booster armature, with only one of them controlled (Fig. 12·7).
2. The voltage to be regulated may alone have a booster winding.
3. The voltage to be regulated may be generated entirely in the windings of the booster armature.

The third method is practical only for low voltages because of the large number of turns and the relatively high field current that would be required to generate a high voltage. In any case it is less practical to regulate the highest voltage output because it is necessary to use resistors in the regulator coil circuit to limit the current, and at high voltages the loss would be excessive. Furthermore, it is less important to regulate the higher voltages because this can readily be done by regulating circuits in the radar set itself. The demagnetizing field is used to allow the

carbon-pile regulator to operate in the region of optimum performance. Choice of one of the foregoing methods depends on the requirements of the device with which the dynamotor is to be used.

Over ranges of input voltage of from 25 to 29 volts and from no load to full load on the dynamotor, the regulation will be approximately 3 per cent. The addition of the booster armature and regulating field will, of course, increase the size and weight of the dynamotor, but the regulator itself can be considerably smaller than a series regulator because it carries only the field current rather than the line current.

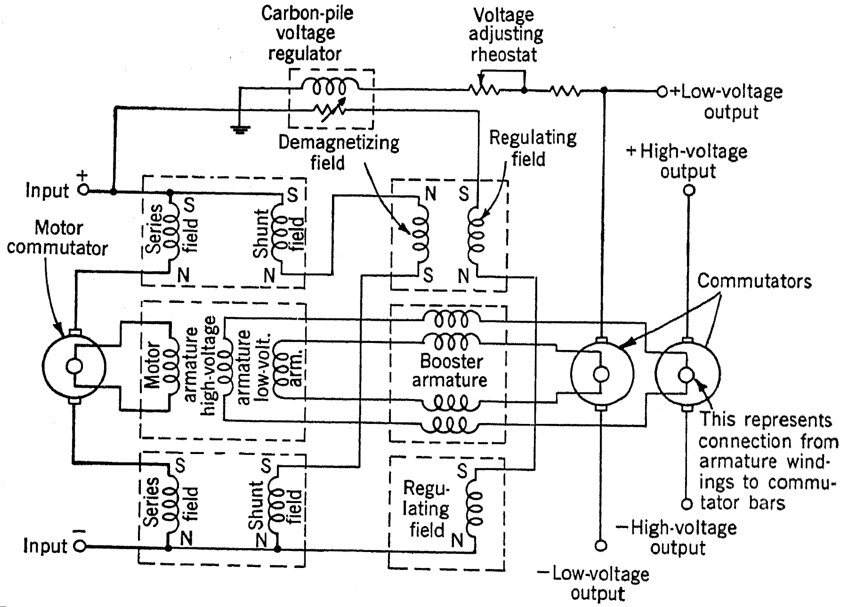


FIG. 12·7.—Schematic diagram of dual-output dynamotor with booster windings and regulating field.

At high altitudes, brushes of the larger dynamotors present the same problem as inverter brushes and should be treated as discussed in Sec. 12·8. The smaller dynamotors do not generally give brush trouble as the current densities are much less.

12·8. Inverters.—When the available power supply is direct current and the voltage or power requirements of the power-using equipment are greater than can be supplied by dynamotors, it becomes necessary to use inverters or motor-alternator sets to furnish a-c power. This section covers only those aircraft inverters with which the Radiation Laboratory has had experience, but it is believed that this experience is typical and that the information presented here is applicable to other problems of the same type.

Aircraft inverters are built with outputs of 100 to 2500 va, usually at approximately 400 cps to 800 cps although other frequencies are occasionally used. The Army has adopted a nominal frequency of 400 cps as a standard for its airborne equipment, while the Navy uses 800 cps. The weight-saving in magnetic components and filter condensers is approximately 50 per cent in going from 60 to 400 cps, but the further saving in going to 800 cps is negligible and the choice of these two frequencies by the two Services was more or less arbitrary. The British use frequencies of 1400 to 2800 cps, at which any saving of weight is questionable, and alternator design is made more difficult because of the large numbers of poles and the high speeds involved.

An aircraft inverter consists of a 27·5-volt d-c motor, either shunt- or compound-wound, direct-connected to an a-c generator and mounted in a common frame. Strictly speaking, in an inverter the field windings are common to both units and the armature windings may or may not be common, whereas in a motor-alternator the two units are electrically and magnetically separate except for the fact that the alternator field is usually fed from the same d-c supply that powers the motor. Both types are commonly referred to as "inverters," however, and that usage will be followed here.

In most inverters the alternator field is on the rotor, although this is by no means always the case. Most inverters use conventional salient-pole wound fields, but the 800-cps inverter of Table 12·2 uses an inductor-type field. The most popular aircraft inverters in current use are listed in Table 12·2. For all the units of Table 12·2 the input voltage is nominally 27.5 and the output is 115 volts. Efficiencies are approximately 50 per cent. Some of these units are shown in Figs. 12·12, 12·13, and 12·17.

Some of the principal problems encountered in inverter operation are

TABLE 12·2.—AIRCRAFT INVERTERS

Type designation	Maker	Capacity, va	Frequency, cps	Phase	Weight, lb	va/lb
12123-1-A..	Eclipse	100	400	3	..	....
12121-1-A..	Eclipse	250	400	1 or 3	13	19.2
10596......	Leland	500	400	1	23	21.8
PU-16.....	Wincharger	750	400	1 or 3	38	19.8
800-1-C....	Eclipse	840*	800	1	32	26.2
PE-218-C.. / PE-218-D..	Leland / GE	1500	400	1	55	27.2
PU-7......	Airways	2500	400	1	75	33.4

* This is the name-plate rating. Tests have indicated that this unit will carry 1000 va with blast cooling and at altitudes of less than 10,000 ft. The weight figure includes an external r-f filter and a 12-μf compensating condenser. The 1000-va rating increases the output to 31.3 va/lb.

those of waveform, voltage regulation, excessive starting current, brush wear, and speed regulation.

Waveform.—Because most a-c power used in electronic equipment is either converted to direct current or used for heating, there is usually no inherent requirement for sinusoidal wave shape. (One exception to this statement is furnished by a-c resonant-charging radar modulators, which must be furnished with power of low harmonic content.) With most inverters, however, the output waveform may vary radically with changes in load. Since a stable d-c voltage is the final requirement in most electronic power supplies, it is necessary to maintain a fixed ratio between the a-c maximum voltage and the rms voltage, which ratio is called the "crest" or "amplitude factor." The output voltage of rectifier circuits employing condenser-input filters depends upon the crest voltage. For rectifiers employing choke-input filters, the ratio of rms voltage to average voltage is important; this ratio is called the "form factor." These two ratios should be as constant as possible under all load conditions. This requirement is most easily met by alternators with low subtransient reactance. Practically, it is preferable to employ conventional salient-pole rotating-field alternators operating at 400 cps rather than high-impedance inductor alternators operating at higher frequencies. Although the reactance of such an inductor alternator can be neutralized by a series capacitance (as is done in the Model 800-1-C Bendix 800-cps motor-alternator) such balance is completely effective only at one value of load impedance. Changes in load cause changes in wave shape; hence, even if the voltage regulator operates perfectly and maintains a constant average or a constant rms voltage, the d-c output of power supplies fed from the alternator may vary excessively. Fig. 12·8 shows how the wave shape of a typical aircraft alternator may vary with varying load.

Besides the variation in waveform with changing load, individual machines of the inductor-alternator type show wide variations in characteristics. Crest factors measured for different machines of the same type have varied from 1.15 to 1.75. When such machines are used, power transformers should be provided with primary taps, and separate filament transformers should be used.

Voltage Regulation.—The problem of voltage regulation of an alternator is discussed in Sec. 12·9 and will not be elaborated here. It should be pointed out, however, that simultaneous regulation of voltage and frequency in a true inverter, in which the motor and alternator fields are magnetically common, can only be accomplished by varying the field to control the output voltage and by controlling the rotor speed by varying the motor armature current. Such a method is hardly practical.

Starting Currents.—When an aircraft inverter is connected directly across the d-c bus of the airplane, it will draw a momentary starting

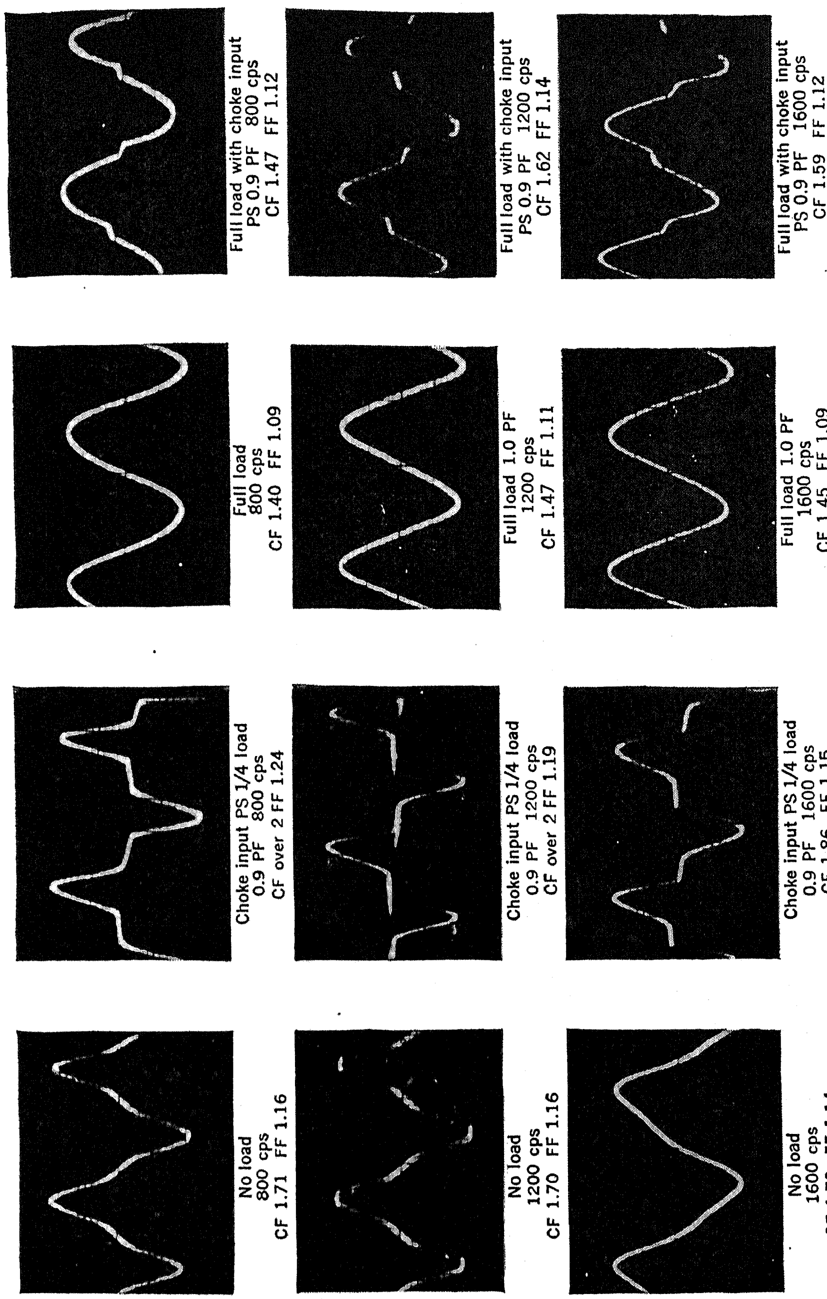


FIG. 12·8.—Voltage waveshape of Eclipse NEA-6 generators.

current of three to four times the rated full-load current. These high starting currents cause excessive brush wear and also a momentary dip in the bus voltage which may affect other equipment operating on the same bus. This is not usually a serious matter with inverters below 750-va capacity but, with larger sizes, special starting relay circuits must be employed to limit the starting current. One of the most common methods is to start the motor as a compound motor and then to short-circuit the series field, as shown in Fig. 12·9. In this way the initial

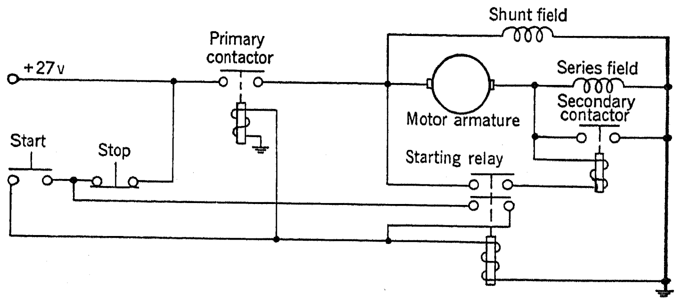


FIG. 12·9.—Motor circuit of 1500- and 2500-va inverters showing starting relay and contactors.

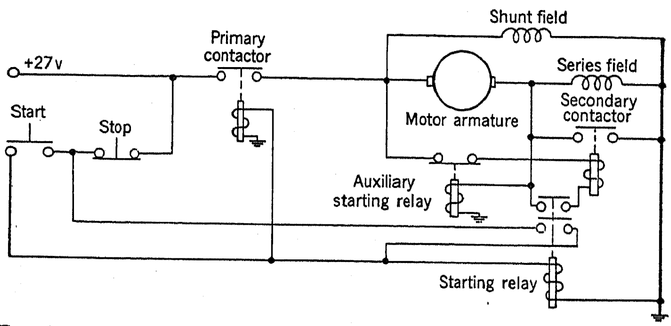


FIG. 12·10.—Addition of auxiliary starting relay to circuit of Fig. 12·9.

starting current is materially reduced, but the current again rises sharply when the secondary contactor closes and before it reaches its steady-state value. Closing of the secondary contactor can be further delayed by using an auxiliary starting relay connected as in Fig. 12·10. The curves of Fig. 12·11 show the reduction of starting current which can be obtained by the use of this circuit.

Brush Wear.—The problem of brush wear has been mentioned in Sec. 12·4 and has been discussed at some length in Chap. 11. The usual remedy for high-altitude brush wear consists of treating the brushes with a compound that liberates oxygen at the operating temperature of the brushes, thus helping to maintain the lubricating oxide film on the commutator. Another treatment is the incorporation of a metallic

halide in the carbon mixture of which the brush is made. Lead iodide, which also produces a lubricating film, is the metallic halide ordinarily used. Even with the high-altitude treatment, however, brushes seldom last longer than 300 to 400 hr at 20,000 ft, as compared with at least 1000 hr at sea level. The value of the treatment is shown by the fact that an untreated brush will last only about 4 hr at 20,000 ft.

Speed Regulation.—The output frequency of an inverter is directly proportional to its speed, which may vary over a wide range with variations of input voltage, load, altitude, and temperature. At high alti-

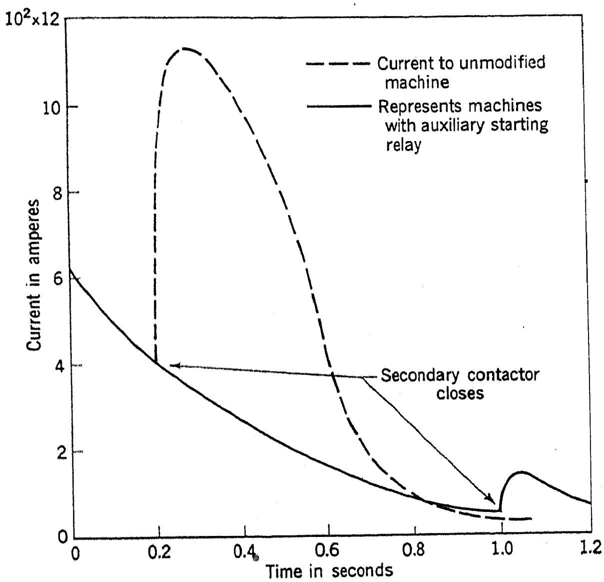


FIG. 12·11.—Starting current of 1500-va inverter, Signal Corps Type PE-218-D. No load on inverter.

tudes, low temperatures and air densities are encountered. The low temperature tends to lower the speed by reducing the resistance of the motor speed, while the reduced air density tends to allow it to increase because of the lower windage losses. Table 12·3 summarizes the results of tests on the 1500-va PE-218-C and PE-218-D inverters. From the table it can be seen that the variation in frequency on changing the input voltage from 29 to 26 was 76 cps, or 17 per cent for the PE-218-C, and 49 cps or 11.5 per cent for the PE-218-D. The latter machine has a compensating resistor in series with the field, which accounts for its somewhat better regulation. It also has an adjustable resistor that allows the frequency to be varied over a range of about 40 cps. The two machines are shown in Figs. 12·12 and 12·13.

In many electronic applications a ± 10 per cent variation in frequency

is not objectionable, but certain indicator and computer circuits require much closer regulation (± 2.5 per cent or better). Good speed regulation

TABLE 12·3.—INVERTER SPEED VARIATIONS

Input voltage	Load	Temperature, °C.	Altitude, ft	Leland PE-218-C, cps	GE PE-218-D, cps
28.5	$\frac{1}{4}$	−15	35,000	485	458
28.5	Full	−35	0	401	392
26	Full	−45	0	373	379
26	Full	25	0	396	396
26	Full	55	0	406	398
29	Full	−45	0	411	404
29	Full	25	0	443	423
29	Full	55	0	449	428

also greatly decreases the difficulty of obtaining good voltage regulation, particularly with most types of saturating-transformer or resonant-circuit a-c regulators. In accordance with the need for better speed

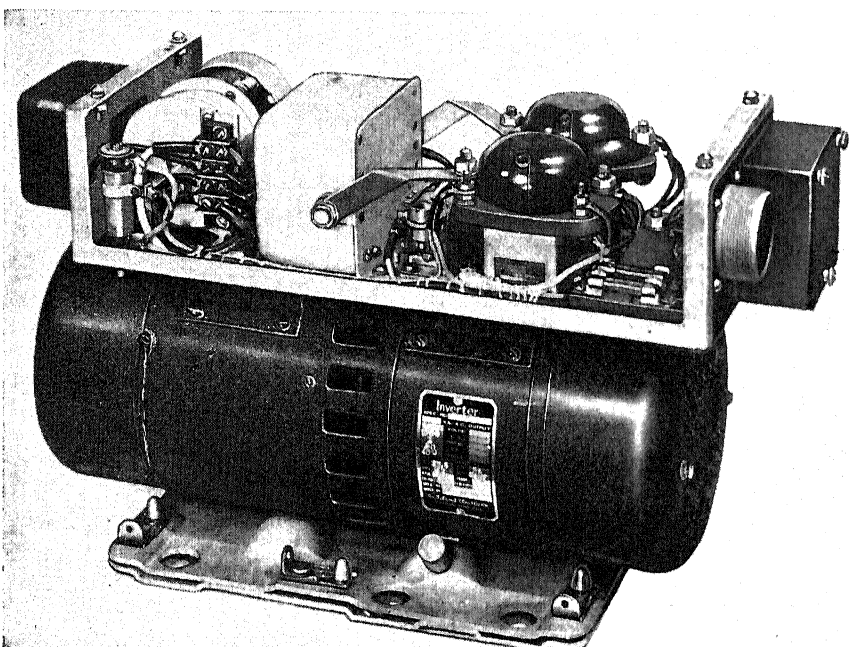


FIG. 12·12.—Leland Electric Company aircraft motor alternator with regulator.

regulation of inverters the latest applicable specifications (AN-I-10) permit a maximum frequency range of 390 to 410 cps for an input varia-

tion of 26 to 29 volts and a temperature range of $-10°$ to $+10°C$ and one-third full load. For the wider ambient temperature range of $-55°$ to $+70°C$ the range may be 380 to 420 cps. Table 12·4 gives the fre-

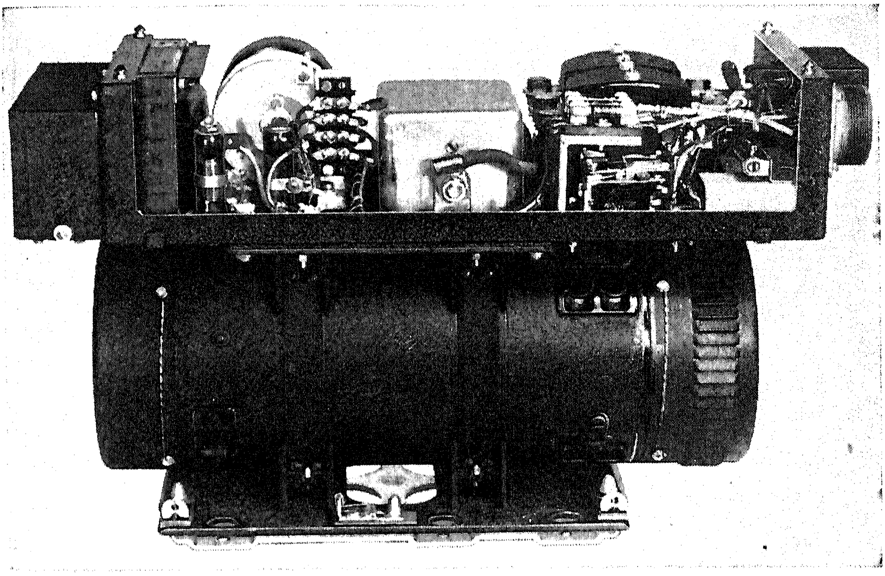


FIG. 12·13.—General Electric Company aircraft motor alternator with regulator.

quency range of the inverters now in general use, with an indication in the "remarks" column of the type of motor or speed control used. All data in the table were taken at 25°C and at sea level.

TABLE 12·4.—AIRCRAFT INVERTER SPEED REGULATION

Make and type	Rating, va	Frequency		Remarks
		At full load (26 v), cps	At ⅓ load (29 v), cps	
Eclipse 12123-1-A	100	410	410	Lee governor
Eclipse 12121-1-A	250	400	410	Lee governor
Leland 10596	500	395	475	Compound-wound
Wincharger PU-16	750	390	403	Carbon pile
Holtzer-Cabot MG-153	1000	340	395	Resonant
Leland PE-218-C	1500	395	450	Shunt-wound
GE PE-218-D	1500	395	440	Shunt-wound
Airways PU-7	2500	410.	410	Regulating field
Eclipse 800-1-C*	840	730	900	Compound-wound

* Nominal rated frequency 800 cps.

The Lee speed regulator, which has been discussed in Chap. 11, is a centrifugal device which alternately opens and closes a short circuit across a fixed resistor which is in series with the motor field. The short-circuiting contacts are on the centrifugal device and can be set to open and close at any predetermined speeds within 5 per cent of each other. The speed regulation is therefore good, as it can be maintained at 5 per cent over all. The principal disadvantages of this type of governor are that it creates a good deal of radio interference, which is difficult to

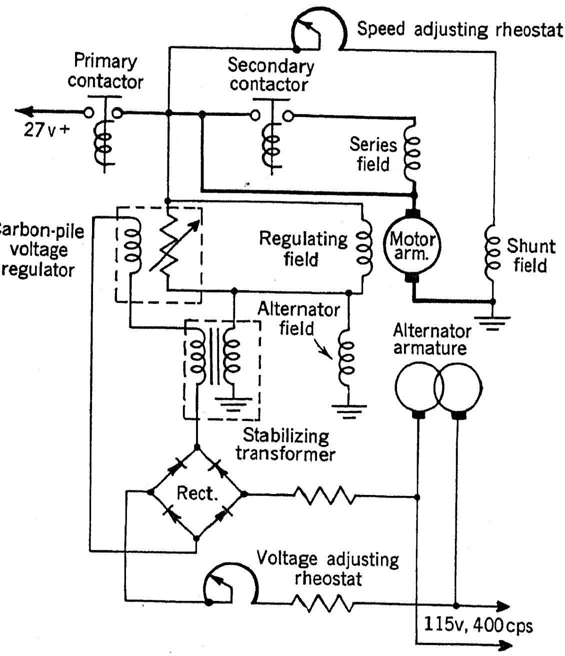


FIG. 12·14.—Schematic circuit of Airways PU-7 aircraft motor alternator, 2500 va, 115 volts, 400 cps.

suppress, and that it causes a pronounced modulation of the output voltage.

Speed regulation can also be accomplished by means of a regulating field controlled by the generator voltage regulator. This method is used in the Airways 2500-va Type PU-7 inverter shown schematically in Fig. 12·14. As the input voltage or the inverter load changes, the resistance of the carbon pile in the voltage regulator varies to maintain constant output voltage. This also serves to vary the current through the motor regulating field in such a way as to maintain constant speed. The motor is designed to have the proper division of flux between the main field and the regulating field. The resistances of the regulating field and of the alternator field must have the proper relation to the

normal range of resistance of the carbon pile in order to obtain good speed regulation.

If the regulator is removed from the circuit the alternator will still generate a voltage because its field current will be supplied through the regulating field. In the case of inverters without the regulating field, removal of the regulator from the circuit kills the output voltage.

In order to get good results from the use of a regulating field the motor-field structure must be operated below saturation, which requires a heavy magnetic circuit. The method was tried several years ago in

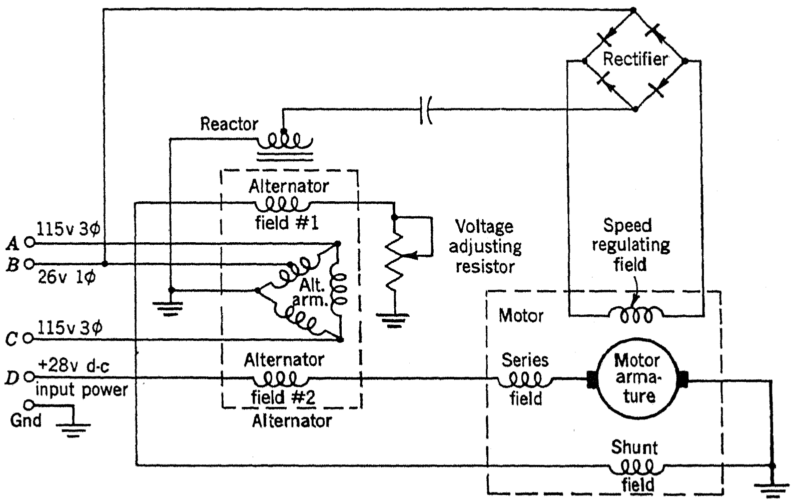


FIG. 12·15.—Schematic circuit of Holtzer-Cabot MG-153 aircraft motor alternator, 750 va, 115 volts, 400 cps, 3-phase; 250 va, 26 volts, 400 cps, 1-phase.

the Leland 1500-va PE-218-A inverter, but was not successful because the emphasis at that time was on weight reduction at the expense of performance. At the present time the only inverter using the method is the Airways PU-7.

An interesting method of speed control (shown schematically in Fig. 12·15) has been used by the Holtzer-Cabot Electric Company in their MG-153 inverter. The reactor and condenser, connected in series with the rectifier that energizes the regulating field, are designed to resonate at a frequency well above the rated frequency of the alternator (in this case 400 cps). The circuit therefore operates on the low-frequency side of the resonance curve; any change in speed will alter the reactance of this circuit and thus vary the field current in the correct direction to provide speed regulation. Should the motor attain a speed that would generate a frequency above resonance, the reverse action would take place, and the speed would continue to increase until limited by friction and windage losses.

The same basic idea was used in a more elaborate form in the 1920's in the Stoller drive for the early Western Electric sound-motion-picture projectors; extremely close speed regulation was attained, but the system was cumbersome, complicated, and relatively inefficient.

The most recent method of aircraft-inverter speed regulation is the use of a centrifugal carbon-pile governor introduced by the Holtzer-Cabot Electric Company. A cross section of this device is shown in Fig. 12·16 and it is shown in Fig. 12·17 mounted on a PU-16 inverter. The electrical circuit used with the governor is shown in Fig. 12·18. A centrifugal device mounted on the end of the inverter shaft acts against

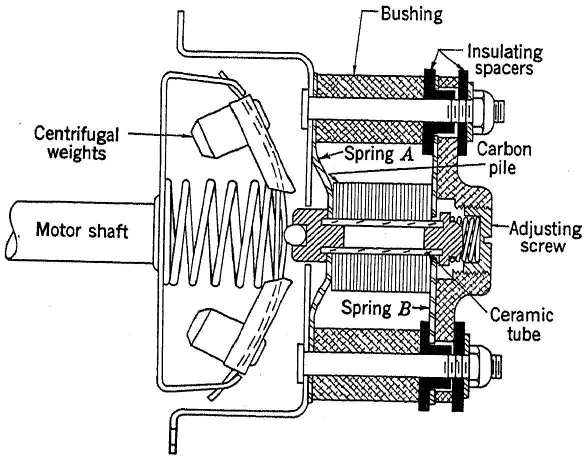


FIG. 12·16.—Holtzer-Cabot Electric Company carbon-pile speed governor.

the carbon pile in such a manner that increased speed will reduce the pressure on the pile and reduced speed will increase it. As may be seen from Fig. 12·16, when the machine is at rest the pile is held in compression by the large coil spring in the rotating element. The resistance is then a minimum, giving maximum field for good starting characteristics. As the machine speed increases, the centrifugal weights compress the spring and reduce the pressure on the pile, increasing its resistance. Should the machine increase its speed sufficiently to decrease the pressure on the ball to zero, the pile will still have some residual pressure from the spring under the pile adjusting screw. This helps to keep the motor from running away and protects the pile from the burning which usually results from too great a decrease of pressure when voltage is still applied to it. At rated speed the pile is balanced between the two springs, and a slight change in speed will cause a relatively large change in resistance. The two laminar springs A and B serve to position the tube holding the pile

12·9. Vibrator Power Supplies.—Vibrator power supplies are particularly suited to applications requiring power up to approximately 150

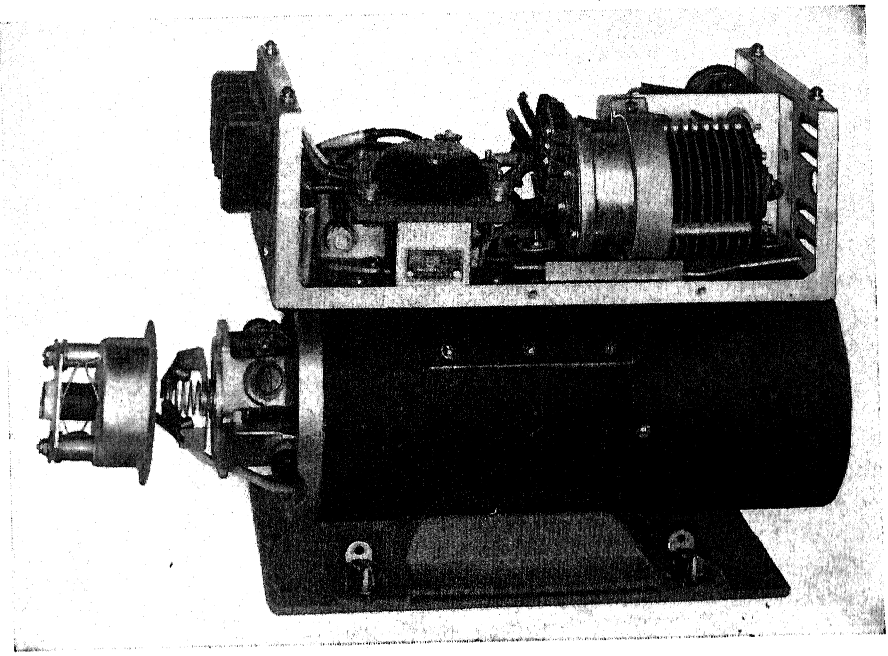


FIG. 12·17.—Wincharger Corporation aircraft motor alternator with Holtzer-Cabot speed control.

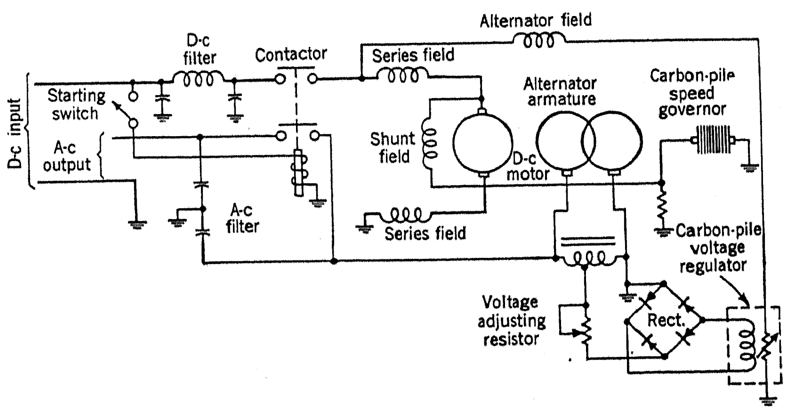


FIG. 12·18.—Schematic diagram of Wincharger PU-16 aircraft inverter, 750 va, 115 volts, 400 cps.

watts, especially in cases where this power is needed at several different voltages. Conventional vibrators, of the type used in auto radios, can supply square-wave a-c outputs up to about 40 watts. So-called "power

vibrators" can handle powers up to 4 or 5 times as great, and heavy-duty units, usually involving several vibrators operated either separately or in synchronism, can handle up to a kilowatt or more, although such large outputs have been comparatively rare.

The chief advantage of a vibrator power supply over a dynamotor is the fact that by its use it is comparatively easy to supply several different outputs from a single unit; thus a single vibrator and transformer with the appropriate rectifiers and filters might supply at the same time 5 ma of direct current at 2500 volts for a cathode-ray tube, 5 ma at 150 volts for bias, and 100 ma at 250 volts for plate supply, the whole unit weighing 6 to 8 lb and operating from a 6- to 24-volt battery supply with an efficiency of 50 to 60 per cent. Another advantage is that since a vibrator supply is composed of a number of small, mechanically independent units it can be built into the same assembly to which it supplies power. Vibrators have suffered in the past from a largely unjustified reputation for poor dependability, but their popularity has been growing rapidly during the last few years and the future will see them much more generally employed than has been the case so far.

The principal disadvantage of a vibrator power supply is that it is difficult to regulate its output voltage except by the use of comparatively inefficient series-tube regulators in the output leads. In calculating efficiency it is also necessary to take into account the power necessary to heat the rectifier and regulator-tube cathodes, since this power must usually be supplied by the vibrator transformer; where a number of d-c output voltages are required the cathodes may use up a large part of the available power.

Vibrators may be divided into three classes on the basis of power output. Small vibrators of the automobile radio class usually have a single pair of input-power–handling contacts and can handle powers up to about 50 watts. Powers up to several hundred watts can be handled by the so-called power vibrators, which usually have several pairs of contacts. The input current must be divided equally between the several pairs of contacts, either by accurate contact setting, by equalizing resistors or chokes, or by multiple transformer primaries with a single pair of contacts feeding each primary. The method using no equalizing resistors gives the best rectification or a-c output. Cold-cathode gas-tube rectifiers are particularly well adapted to use with vibrators, and require no heater power. Contact rectifiers have not been much used in this field because of their high cost.

The voltage regulation of a vibrator power supply is approximately 20 to 25 per cent for d-c output and 15 to 20 per cent for a-c output. Frequency variations are usually small. The frequency of most vibrators is set between 100 and 125 cps, but there is a trend toward higher fre-

quencies. Several types of vibrators are now made with a frequency of 180 cps, which permits a weight-saving in the transformer and filter of about 25 per cent, but they have not been particularly successful because of their short life. Vibrators have also been made for operation at 400 cps, but at this frequency the problems of contact life and of clean make and break without excessive bounce are extremely difficult and have not yet been solved satisfactorily.

The output waveform of a vibrator transformer is a poor approximation to a square wave. At the cost of efficiency, vibrator power supplies can be built which have good voltage regulation and a sine-wave output. The waveform, however, usually changes with changes in load.

Vibrators are relatively immune to changes in temperature, and if enclosed in a hermetically sealed case are also immune to changes in atmospheric pressure.

The weight of a vibrator power supply varies between wide limits, depending upon output, number of separate outputs, degree and type of filtering, method of packaging, etc. Outputs of from 4 to 6 watts/lb can be expected from usual types of units.

Vibrator power supplies are considerably cheaper than their principal competitor, the dynamotor, especially in the lower power ratings. Dynamotors have better voltage regulation, as a rule, and are preferable for low-voltage high-current outputs. For output voltages over 1000 to 1200, dynamotors are usually out of the question because of commutation and insulation difficulties. Dynamotors are heavier than vibrators and although they do not require as much low-frequency filtering they create a particularly vicious form of radio interference that is usually much harder to eliminate than the "hash" of the ordinary vibrator. Dynamotors are relatively vulnerable to unfavorable climatic conditions and require considerable maintenance. The argument as to the short life of vibrators is not particularly cogent, since a plug-in vibrator is as easy to replace as a vacuum tube. Vibrators are finding a rapidly increasing field of application, not only in mobile electronic equipment but also in fluorescent lighting of aircraft and trains, for portable low-powered electrical equipment, for control devices, and for furnishing small amounts of a-c power in districts where only direct current is available.

12·10. Vibrator Construction.—Basically, a vibrator is a vibrating single-pole double-throw switch. A typical low-power vibrator is shown in Fig. 12·19 and a larger unit in Fig. 12·20. A vibrator consists of a steel reed carrying one or more pairs of contacts mounted between one or more pairs of stationary contacts. A small soft-iron armature is mounted on the tip of the reed and a driving coil is mounted with its longitudinal axis parallel to the axis of the reed but offset by a small amount. When the coil is energized the armature is attracted and deflects the reed. This

either makes or breaks the driving contacts, depending on the type of drive, and the reed is maintained in oscillation in a manner similar to the operation of the ordinary doorbell.

The contacts are mounted on flat steel springs that allow them to "give" and help to eliminate bouncing. Contact bouncing is highly undesirable because it results in inefficient operation and greatly shortens

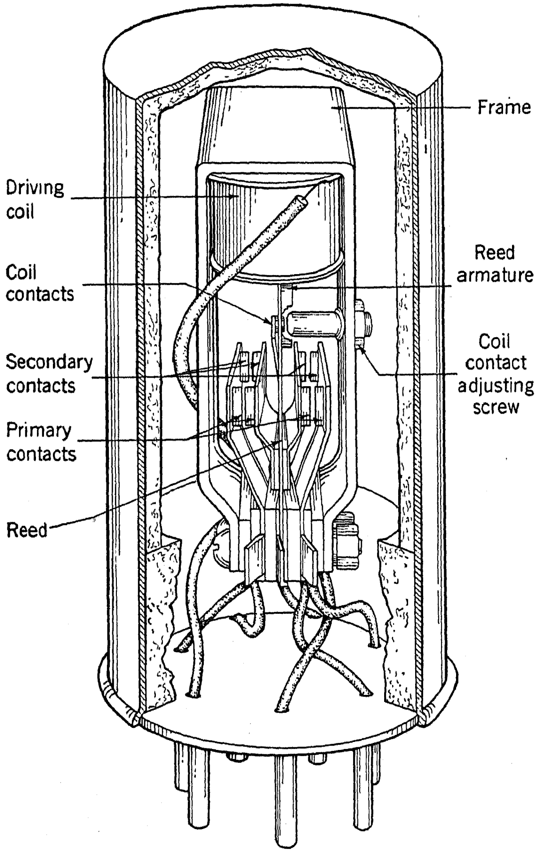


FIG. 12·19.—Typical low-power plug-in vibrator.

the life of the contacts. The slight sliding of one contact over the other which results from the "give" helps to keep the contact surfaces clean but if this movement is too great it will result in excessive wear and short contact life.

The steel reed must be so shaped and mounted as to ensure an even distribution of stresses. This helps to ensure a clean make and break of the contacts and to prevent fatigue cracking of the reed.

The most critical adjustment in a vibrator is the contact spacing.

This determines the length of time the contacts are closed, the symmetry of the voltage wave, and the efficiency of the vibrator. Contact spacing is particularly critical in the case of power vibrators that have several contacts connected in parallel. If the contact spacings are not exactly the same the load will not be equally shared and the contacts will be ruined in a short time.

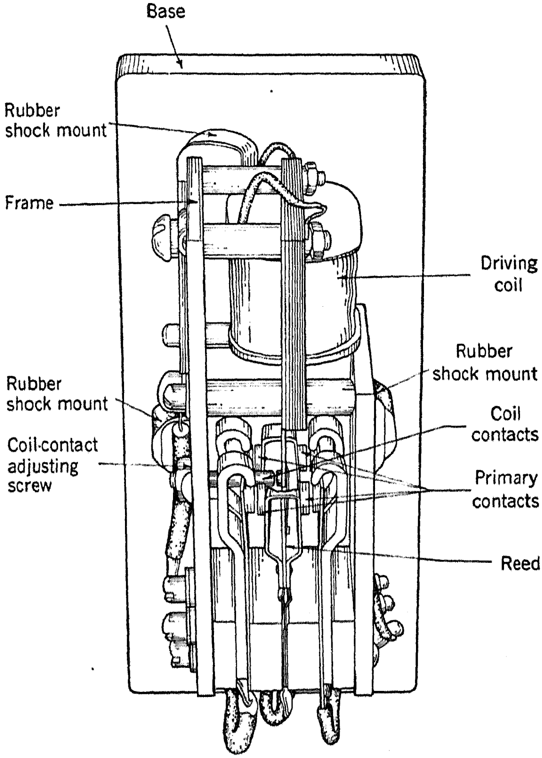


FIG. 12·20.—Typical heavy-duty vibrator.

The life of a vibrator is usually the life of its contacts. Contacts may fail either by burning or by mechanical wear. In an emergency a vibrator that has failed because the contact spacing has been excessively changed by burning or wear may be repaired by respacing the contacts, dressing the surfaces smooth if necessary. The best way to adjust the contacts is to use an oscilloscope on the output of the vibrator transformer, setting the contacts to give the correct output waveform. The process is not particularly difficult after a little experience, but is not ordinarily worth while because the added life will be short at best and a vibrator is a fairly inexpensive piece of equipment.

Driving Circuits.—Most vibrators use either the shunt-drive or the series-drive circuit. In the shunt-drive circuit of Fig. 12·21 the driving

coil is connected across the reed and one contact, and the contacts are normally open. When voltage is applied to the circuit, current flows from the battery through one half of the transformer primary, the driving coil, and back to the battery. The field of the driving coil pulls the reed to the left until the contacts close, which short-circuits the driving coil and permits a much larger current to flow through the left half of the transformer primary. The momentum acquired by the reed causes it to swing past the position of contact closure, carrying the stationary contact with it on its spring. Since the driving coil is now short-circuited there is no force tending to hold the reed to the left and it springs back, opening the contacts on the way and then closing the other pair of contacts. This closure permits a heavy current to flow through the right half of the primary which more than balances the weak current in the left half, and the second half of the output wave is started. The reed continues to swing to the right past the point of closure of the right contact pair, then

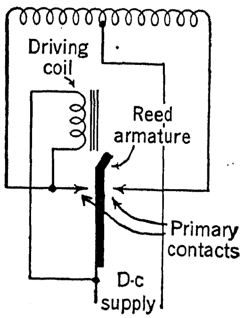


FIG. 12·21.—Shunt-drive vibrator circuit.

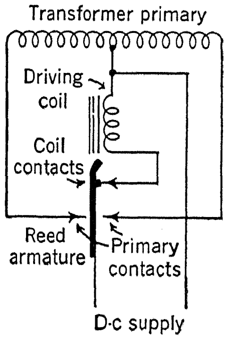


FIG. 12·22.—Series-drive vibrator circuit.

reverses and starts a new cycle. The frequency of vibration is determined principally by the material and construction of the reed.

The shunt drive has the disadvantage of allowing the driving-coil current to flow through one half of the transformer primary while the load current flows through the other half, which results in an asymmetrical voltage wave. This type of vibrator is used extensively in automobile radio power supplies because of its low cost.

In the series-drive circuit the driving coil is connected directly across the d-c supply in series with an extra pair of normally closed contacts. The action is exactly that of the conventional doorbell; energizing the coil pulls the series contacts apart and breaks the coil current, whereupon the reed springs back, the contacts reclose, and the cycle repeats. The series-drive circuit is shown in Fig. 12·22. Its principal disadvantage is the slightly greater cost of the additional pair of contacts, but the separa-

tion of the driving and load currents and the greater ease of adjustment make it decidedly preferable to the shunt-drive type of vibrator.

Mountings.—Almost all small vibrators are mounted in cylindrical metal cans with contact pins at one end to permit plug-in mountings. Some types may be plugged into standard tube sockets but many require special sockets, which are usually fitted with spring clips that snap into embossed grooves in the can when the vibrator unit is plugged in. If standard tube sockets are used, some adequate means of holding the unit into the socket is required to prevent it from working loose because of its own vibration or because of external shocks. The can is lined with a resilient sheath of sponge rubber and the connections from the vibrator to the base pins are made with flexible wire so that the vibrator is mechanically fairly well isolated from the can and chassis. The can must be so designed that its natural vibration frequency is remote from that of the vibrator. Most cheap vibrator cans merely provide mechanical and dust protection for the vibrator, but hermetically sealed types are available for use at high altitudes and in unfavorable climates. Vibrator units may be mounted in any position.

Large vibrators are usually mounted in rectangular metal cans which are often provided with two tube bases on the bottom of the can. The use of two bases separated by a few inches provides a much more rigid support than could be obtained from a single one. The vibrator is usually isolated from the can by rubber shock mounts. The cans may or may not be hermetically sealed, and may be mounted in any position.

Synchronous and Nonsynchronous Rectification.—From the standpoint of the method used for the rectification of the transformer output voltage, vibrators may be divided into two classes, synchronous and nonsynchronous. Nonsynchronous vibrators, also known as "polarity changers," "converters," or "interruptors," have one or more pairs of contacts that act to make and break the primary current only, rectification usually being accomplished by a tube rectifier. They are used for the conversion of direct current to alternating current and for applications for which the synchronous type is unsuitable.

Synchronous vibrators are provided with extra sets of contacts that make and break the transformer secondary current synchronously with the primary make and break, thus acting as synchronous rectifiers. The spacing of the secondary contacts is greater than that of the primary contacts, thus permitting the former to make after and to break before the latter. This action relieves the primary contacts of having to handle the input load current and greatly increases their life.

In most types of synchronous vibrators the input and output circuits have a common point since the reed contacts of both sets are electrically connected through the reed. These types of vibrator are used for low-

voltage power supplies, the maximum voltage being limited by the insulation. Maximum ratings are usually about 300 volts and 100 ma, but special units can be made for much higher voltages.

A form of the synchronous vibrator known as the "split-reed vibrator" has a twin reed the two halves of which are mechanically connected by insulating material. One half carries the primary and the other the secondary contacts. In this type the input and output circuits have no common connection, which permits a wider variety of applications.

12·11. Vibrator Circuits.—If a vibrator is connected across a resistor as shown in Fig. 12·23*a* the resulting voltage wave across the whole

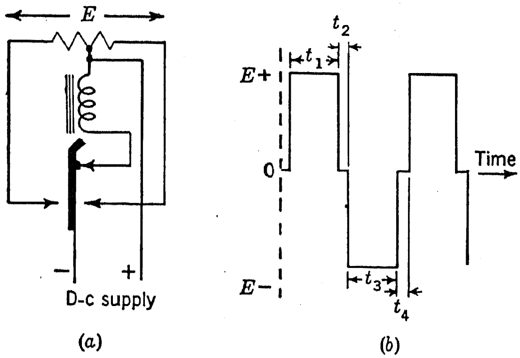


FIG. 12·23.—Vibrator with resistive load.

resistor will appear as shown in Fig. 12·23*b*. In the latter figure, t_1 is the time that the current flows through the resistance in one direction; t_2 is the time during which the circuit is open and the moving contact is traveling from one fixed contact to the other; t_3 is the time that the current flows through the resistance in the other direction; and t_4 is a repetition of t_2 but in the opposite direction. The ratio of the time that the contacts are closed to the total time for one complete cycle,

$$T_c = \frac{t_1 + t_3}{t_1 + t_2 + t_3 + t_4},$$

is known as the "time closure factor" or "time efficiency." It is usually expressed as a decimal or percentage. Present-day vibrators have a time closure factor of 0.80 to 0.95. This value varies with different manufacturers, with different vibrator frequencies, and with aging of the vibrator. For highest efficiency and best results it should be kept as large as possible.

From the time-closure factor the following waveform relationships may be obtained. If E is the applied d-c voltage and T_c is the time-closure factor,

$$E_{\text{avg}} = ET_c \qquad \text{average value of voltage,}$$
$$E_{\text{pk}} = E \qquad \text{peak value of voltage,}$$
$$E_{\text{rms}} = E\sqrt{T_c} \qquad \text{rms value of voltage,}$$
$$F_f = \frac{E_{\text{rms}}}{E_{\text{avg}}} = \frac{1}{\sqrt{T_c}} \qquad \text{form factor,}$$
$$F_a = \frac{E_{\text{pk}}}{E_{\text{rms}}} = \frac{1}{\sqrt{T_c}} \qquad \text{amplitude factor.}$$

When a vibrator works into an inductive load such as the primary of a transformer, however, the voltage wave is very different from that in the resistive case. The transformer requires a 90° lagging magnetizing

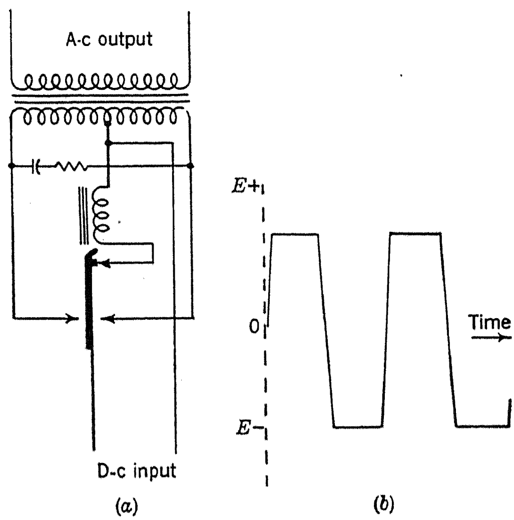


FIG. 12·24.—Shunt vibrator circuit with buffer condenser.

current that can be supplied by the battery while the contacts are closed. When the contacts open the magnetizing current is suddenly interrupted and the magnetic field of the transformer collapses. The energy stored in the field must be dissipated at the contacts, which causes severe arcing and the destruction of the contacts. In order to avoid this condition some means must be provided to supply magnetizing current during the time that the contacts are open. This is done by connecting a buffer condenser of the proper value across the transformer.

If the vibrator is connected to a transformer load with a buffer as shown in Fig. 12·24*a*, theoretically the output voltage wave will appear as shown in Fig. 12·24*b*. When contact is made on one side of the vibrator, current flows through the transformer primary and at the same time the condenser is charged. When contact is broken and the reed is traveling across to the other contact the energy stored in the condenser

is discharged through the transformer, supplying the needed magnetizing current. Contact is then made on the other side and the other half of the cycle is completed.

Fundamentally, there are two types of vibrator circuits: the shunt circuit of Figs. 12·24*a* and *b* and the series circuit of Figs. 12·25*a* and *b*. Due to manufacturing tolerances in transformers, condensers, and vibrators, and to changes due to aging of the vibrator, the actual output waveforms will differ somewhat from those shown in Figs. 12·24*b* and 12·25*b*.

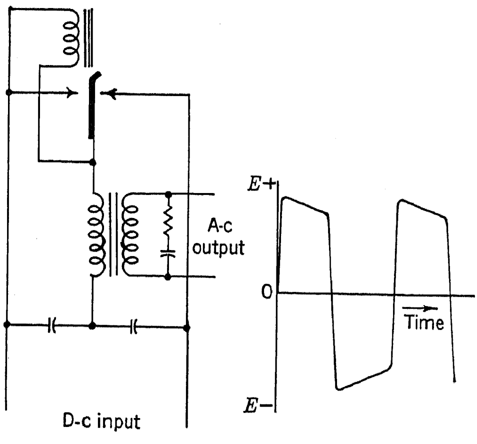


FIG. 12·25.—Series vibrator circuit.

The waveform of a vibrator supply varies greatly with the amount and type of load. It is possible by the use of suitable capacitance, inductance, resistance, and transformer design to obtain almost any type of waveform, but at a sacrifice of efficiency.

Design Considerations.—The design of any one component of a vibrator power supply is complicated by the fact that its design is dependent upon the other components associated with it. The most complicated and important—and the least understood—is the vibrator transformer. The voltage induced in any winding is given by Eq. (1) of Chap. 4;

$$E = 4 \times 10^{-8} f N F_f A_c K_s B_{\max},$$

where

E = induced voltage, volts,
f = frequency, cps,
N = number of turns in coil,
F_f = form factor of voltage wave,

A_c = overall core area, cm²,
K_s = stacking factor,
B_{max} = maximum flux density, gauss.

Since the form factor of a vibrator wave shape is $F_f = 1/\sqrt{T_c}$, the induced voltage formula becomes

$$E = 4 \times 10^{-8} \frac{fNA_cK_sB_{max}}{\sqrt{T_c}}.$$

In normal power-transformer design at low frequencies the operating flux density is approximately 80,000 lines per square inch.

In a vibrator transformer design, the flux density is kept to a maximum of 50,000 lines per square inch for a relatively long vibrator life. The actual value used depends upon the shape of the saturation curve of the core material used. This low value of flux density must be used because when the vibrator first starts the total flux in the transformer is double the steady-state flux.

It is well known that conventional power transformers operating on sinusoidal alternating current are subject to an inrush current that may reach ten times the normal full-load current. The magnitude of the inrush current depends on the instantaneous value of the voltage when the circuit is closed and upon the steady-state maximum flux density and the saturation characteristics of the magnetic core material.[1] Assuming the worst condition, that the circuit is closed at the instantaneous value of voltage which results in the maximum transient inrush current, the flux will rise to a maximum of approximately twice the steady state.

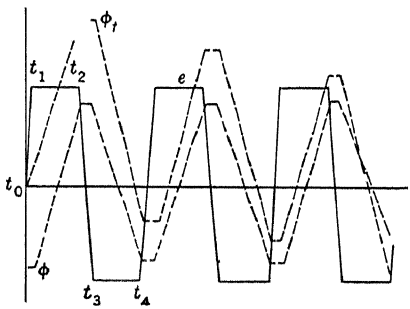


FIG. 12·26.—Voltage and flux in vibrator transformer.

A vibrator transformer may be analyzed in a similar manner, taking into consideration the fact that the impressed voltage is mechanically switched direct current that approximates a square wave. In this case, the maximum transient value of the flux always reaches approximately twice the steady-state maximum flux, and the maximum value of the inrush current will be twice the steady-state maximum current, or more, depending on the flux density and the saturation curve of the magnetic material.

An idealized drawing of voltage e, transient flux ϕ_t, and steady-state flux ϕ is shown in Fig. 12·26. To simplify the analysis, the effect of

[1] R. R. Lawrence, *Principles of Alternating Current Machinery*, 3rd ed., McGraw-Hill, New York, 1940, pp. 186–190.

residual magnetism has been omitted. When the vibrator is energized, contact is made at t_1, and the current and flux start to build up according to the exponential function $i = \frac{e}{r}(1 - \epsilon^{-\frac{r}{L}t})$. The flux ϕ_t is shown in Fig. 12·24 as a straight line because the closure time $t_1 - t_2$ is very short compared with the time required for the current to build up when approaching the limiting value e/r. The contacts break at t_2 and the circuit is open until the other contacts make at t_3. No decay of flux is shown during the interval $t_2 - t_3$ because the current is maintained by the buffer condenser. (In practice there is some decay of flux during the open-contact period but it is not usually more than 5 to 10 per cent.) The other contacts are energized from t_3 to t_4 and the flux is built up in the reverse direction in the same manner.

After a few cycles the flux becomes symmetrical about the time axis because of the losses in the iron and copper circuit in the same manner as in conventional power transformers operated on sinusoidal alternating current. The steady-state flux is shown by ϕ in Fig. 12·26. This analysis is made on the assumption that the forward-contact closure time is equal to the back-contact closure time and that the closure times are the same during the first cycle as during the steady state. This, of course, is not true in the practical case, but although it is probable that the closure times during the first several cycles are somewhat shorter than during the steady state, there is also some contact bounce or chatter. This increases the tendency to contact burning and offsets whatever gain there is from the shorter closure time, which results in less than theoretical maximum flux density and maximum inrush current. Thus at the start the contacts must carry high currents at a time when they are least able to do so. Unless the inrush current is kept down to a satisfactory value, the contacts will be immediately destroyed.

Slightly higher values of flux density can be obtained by winding the transformer primary with a high resistance or by inserting a series limiting resistor, but this means lower efficiency and poor regulation.

An effort should be made to keep the leakage reactance in the vibrator transformer as small as possible. The input leakage reactance of a small power transformer operated with 115-cps sinusoidal input would be a few percent of the primary reactance. Since the square wave normally found in a vibrator transformer contains a high percentage of harmonics, however, the leakage reactance is three or four times greater than it would be with a sine wave of the same fundamental frequency. Leakage reactance can be minimized by completely filling the core window with winding, by subdividing the windings, by properly locating the windings with respect to each other, and by employing as high a space factor as possible.

The transformer must be so designed that the flux density will not exceed the permissible value with a maximum value of applied voltage. This should receive the highest consideration when the vibrator supply is powered from a battery-generator combination. The voltage actually applied to the transformer primary is the input d-c voltage minus the drop through the switch, fuse, and vibrator contacts. If the supply has a delayed load such as a heater-type rectifier, the voltage impressed on the transformer primary at the start will be higher than when running under load. Any a-c measurements on the vibrator supply should be made with thermocouple meters. Because of the presence of harmonics most other types of meters will not give correct readings.

Thin laminations should be used to keep the magnetizing currents to a minimum. The thickness should not exceed 0.014 in. and preferably 0.007-in. laminations should be used. The stacking factor should be high and the air gap kept to a minimum.

The output-voltage waveform of a vibrator is far from sinusoidal. If a vibrator is to be used as a standby source of power equipment which normally operates from the regular 60-cps lines, the differences in waveform and frequency should be taken into account in the design of the equipment.

Although the value of the buffer capacitance can be calculated, it is so easy to obtain its value by trial and error that this method is universally used. In the shunt-type circuit this condenser may be connected either across the transformer primary or across the secondary. Best results will usually be obtained by connecting the capacitance across the primary. When connected across the secondary the reflected capacitance will be adversely affected by the leakage reactance. A primary buffer condenser cannot always be used for reasons of size, weight, and cost, especially with low input voltages. In such cases the capacitance will have to be connected across the secondary. Another solution is to place capacitance on both transformer windings.

In the series-type circuit, some secondary capacitance should be used but the main capacitance must be in the primary circuit. Since the value of capacitance required is inversely proportional to the square of the voltage, large capacitance is needed at low input voltages. For reasonable size and weight, electrolytic condensers must be used, but since this type of capacitor has adverse temperature characteristics its use involves voltage and temperature limitations.

This value of capacitance depends upon the core-material characteristics, the vibrator frequency, and the contact-closure factor. Transformer iron with a high magnetizing current requires a large capacitance, and vice versa. The higher the vibrator frequency and the greater the contact-closure factor, the less capacitance is necessary.

Since the vibrator frequency decreases with age and the contact-closure factor decreases because of contact wear, the value of capacitance used should be somewhat greater than needed for a new vibrator.

As the vibrator contacts wear, "spikes" will appear on the voltage wave. To prevent breakdown under this condition and with high no-load output voltage the rating of the buffer condenser should have a sufficiently high safety factor.

A resistor should always be connected in series with the buffer condenser to limit the current and to minimize the steep wavefront.

Rectification of the a-c output of a vibrator is usually accomplished by tubes, synchronous contacts in the vibrator, or dry-disk rectifiers.

Synchronous contact rectification is ordinarily limited to approximately 300 volts at 100 ma. This type of rectification is used extensively in lightweight low-power supplies. It has a high efficiency, but introduces r-f interference that is difficult to eliminate.

Cold-cathode rectifiers are used for low-powered supplies. The voltage characteristics of a vibrator supply are well suited for the operation of this type of tube. It has the disadvantage that a minimum current is required to keep the gas ionized. For this reason it cannot be used for loads that will draw less than approximately 35 ma. A bleeder can be used to satisfy this condition, but at a loss of efficiency. Contact rectifiers have been used only to a slight extent because of their high cost.

Heater- and filament-type rectifier tubes are used extensively because of their versatility, their low cost, and their ease of maintenance. Heater-type tubes in which the filament is not directly tied to the cathode have been developed especially for vibrator power supplies. The r-f interference problem is minimized when using these tubes. Another advantage is that, when a power supply using this type of rectifier is first turned on, the vibrator contacts will carry only the magnetizing current. There will be no load current until the cathode is heated up. Thus, during the first few cycles at starting when the contacts are already overloaded, they will not be further overloaded by the load current.

All rectifiers should be of the full-wave type. Half-wave rectifiers should never be employed unless the amount of half-wave power is a very small percentage of the total power used. This limits half-wave rectification to bias usages. It is impossible to obtain the proper value of buffer condenser when using this type of rectifier because, if the value is correct for the half cycle when power is drawn from the transformers, it will be too great for the other half cycle. This means that the vibrator life will be shortened.

For many applications adequate filtering can be obtained by using a condenser filter. The output wave of the rectifier will be approximately

a square wave, and less filtering will be needed than if the wave were sinusoidal.

The suppression of r-f interference in a vibrator power supply is a complex problem. Methods that work in one case may fail entirely in another. There are some things that can be done that will always minimize the r-f disturbance, but to completely eliminate it cut-and-try methods must be used.

All components should be fully shielded magnetically and electrostatically. Special consideration should be given to the proper location of components and leads. Leads should be as short as physically possible and twisted or shielded. Primary and secondary circuits should be isolated from each other. A good electrical ground should be provided and one side of the input and output circuits should be grounded. The

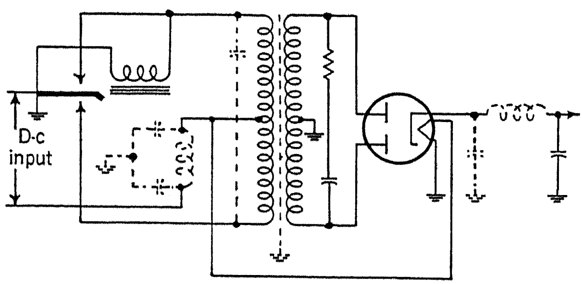


FIG. 12·27.—R-f interference suppression in vibrator power supply. (Dotted lines show r-f suppressors.)

use of a larger input choke than necessary should be avoided as it may result in more r-f interference than would be present without it.

Figure 12·27 shows a vibrator circuit with the typical r-f interference suppressors. Other suppressors may be needed depending on the amount of r-f interference that is present and the amount that can be tolerated.

REGULATORS

12·12. Generator-voltage Regulators.—Regulation of the output voltage of a generator is usually accomplished by changing the field current with a suitable variable resistor to compensate for changing load, temperature, or speed. This change may be made manually in applications where the load is constant and the speed of the generator varies slowly or not at all, but in many cases manual regulation is impracticable and some form of automatic regulator must be employed.

Mechanical Regulators.—The simplest form of automatic generator-voltage regulator is the vibrating-contact regulator. It is essentially a sensitive, rapid-acting contactor with its coil energized by the output voltage of the generator and with a pair of normally closed contacts in

series with the field coil and exciting current supply. In the interests of better operation the contacts are usually shunted by a resistor so that they may vary the field current by only a fraction of its total value. The lower the value of the resistance the less the range of control but the longer the life of the contacts. In operation the regulator armature vibrates continuously, opening and closing the contacts. The ratio of time open to time closed governs the average current through the contacts and thereby controls the average generator voltage.

Vibrating-contact regulators are compact and inexpensive but have not proved satisfactory for service in the field. They have two principal disadvantages: the life of the contacts is very short, and changes in the contact surfaces result in sudden and erratic zero shifts of several per cent of the output voltage. These regulators may be satisfactory for noncritical applications where adequate maintenance is assured, but they have been largely superseded by other types.

A second type of regulator is the so-called "finger-type" regulator such as the Westinghouse Silverstat. This is essentially a multistep field rheostat with a special type of switch controlled by a solenoid which is excited by the output voltage. The switch consists of a number of parallel flexible spring fingers with contacts on the outer ends. An arm actuated by the solenoid presses the fingers together and brings the contacts successively together as it moves. Resistors are connected from each finger to the next and their values are so chosen that each one produces approximately the same change in the output voltage. The motion of the arm is opposed by an adjustable spring, and in operation the plunger of the solenoid floats in a position that is determined by the spring setting. A decrease in output voltage weakens the pull of the solenoid, which permits the plunger to be pulled farther out of the coil by the spring; the resulting motion of the arm presses on the stack of fingers and short-circuits one or more additional sections of the resistor. This action increases the field current and restores the generator voltage to normal. A dashpot or other damping device is connected to the arm to prevent hunting.

When properly installed and maintained finger-type regulators provide satisfactory regulation, but they are not suitable for most applications in the field because of contact troubles. Even in the absence of corrosion the contacts tend to stick and burn, and this tendency is greatly increased by corrosive conditions. The maintenance of finger-type regulators has proved to be impracticably difficult in the field, and they have not been much used in military equipment.

The most widely used type of voltage regulator, at least in military equipment, is the carbon-pile type. The carbon-pile regulator (Fig. 12·28) was first developed in England, where it is known as the Newton

regulator after the inventor. The variable resistance element consists of a stack of carbon disks or annular rings placed in a ceramic or tempered glass cylinder. The cylinder is mounted in a metal housing which serves to dissipate the heat from the pile and gives structural support. One end of the pile rests against a button held in place by radial leaf springs; the other end is retained by a screw usually referred to as the "pile screw" or "pile-adjusting screw."

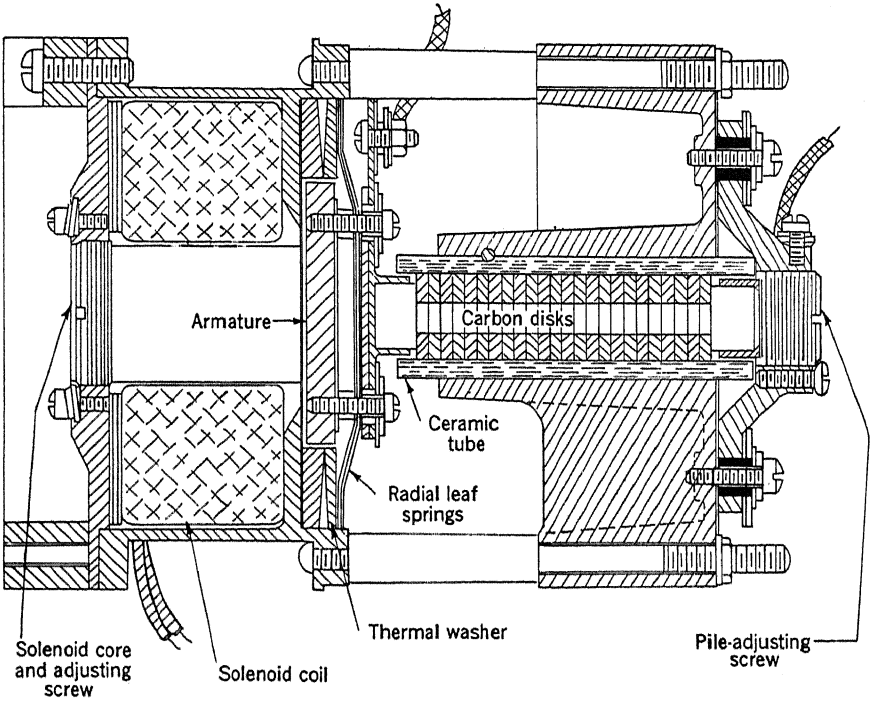


FIG. 12·28.—Carbon-pile voltage regulator (cross section).

The control element of the regulator is a solenoid coil and armature. The current through the solenoid coil is proportional to the voltage to be regulated, and the pull of its core on the armature is proportional to the air gap between the two and to the coil current. The air gap is adjustable by movement of the core; this constitutes one of the adjustments to be made on the regulator.

With the core in fixed position and the pile-adjusting screw tight, the output voltage of the generator will be high. As the pile screw is loosened the voltage will drop, reach a minimum point, rise, and then drop again as shown in Fig. 12·29. The generator will regulate properly to the left of the hump or to the right of the dip. Between these two points, that is, on the downward slope of the curve, regulation will be unstable.

The slope of the curve to the left of the peak is less than that to the right of the valley, giving better regulation. However, in this region the carbon pile is under less pressure and is thus more susceptible to mechanical vibration and shock. Most recent practice, therefore, is to adjust the regulator to operate on the right-hand side of the dip.

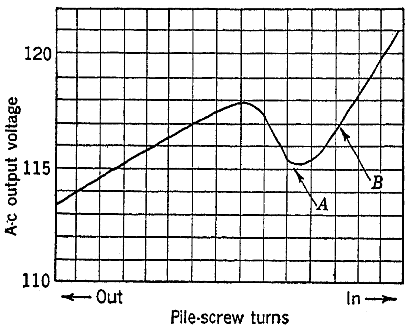


FIG. 12·29.—Carbon-pile regulator adjustment: point A—bottom of dip, 115 volts; point B—optimum operating point, 117 volts.

When carbon-pile regulators were first used on inverters they were mounted directly on the rotating machine. This gave rise to serious troubles because of the susceptibility of the regulator to vibration. Vibration of the carbon pile causes amplitude modulation or "jitter" of the a-c voltage, which in a radar set shows up as "spoking" and blurring of the indicator scope. The frequency of the modulation is normally 30 or 40 cps. The maximum jitter which can be tolerated is about 1 to $1\frac{1}{2}$ volts.

The regulator should be shock-mounted as a separate unit (Fig. 12·30). This procedure, together with adjustment of the regulator on the tight side of the dip, helps not only in clearing up the troubles mentioned above, but also in increasing the interval between regulator adjustments and in reducing the wear of the carbon disks.

The carbon-pile regulator is affected by moisture. Moisture in the carbon pile materially reduces the resistance, and frequently when a motor-alternator is started after having stood for some time the output voltage is high—approximately 135 to 145 volts. After the machine has run for an hour or longer, the moisture is usually driven off and the voltage returns to normal. During this drying-out period the carbon disks are often burned because, as the film of moisture is gradually reduced, it may break down at one particular point on the face of the disk and the high current density at that point may be sufficient to burn the disk. In this event, the regulator pile must be removed and the damaged disk replaced.

One fundamental defect of the carbon-pile regulator is the lack of any means for insuring uniform voltage distribution across the stack. Some carbon junctions may be tightly mated, with low voltage drop; others may be loose, with high voltage drop. If the drop per junction exceeds 1 to 2 volts, sparking may occur which will ruin the pile.

Under changing load conditions, the regulator acts to increase or reduce the field current; as in any action of this kind, hunting may result.

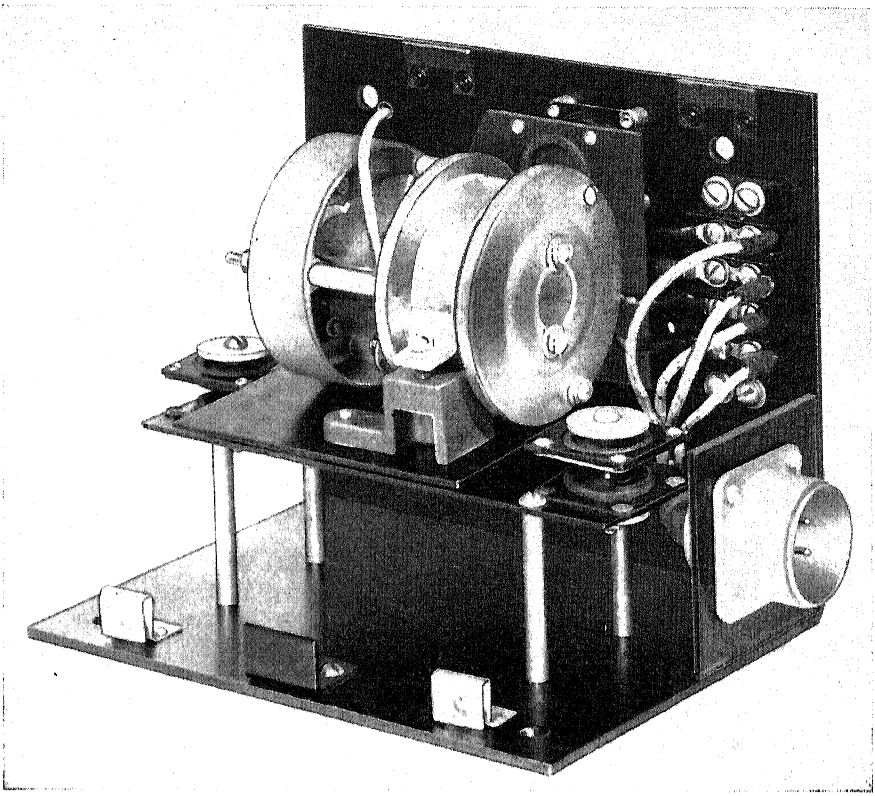


FIG. 12·30.—Typical vibration mount for voltage regulator.

In order to reduce hunting, a stabilizing transformer (Fig. 12·31) is now used with most of the larger alternators. Such a transformer provides a correction depending on the rate of change of excitation.

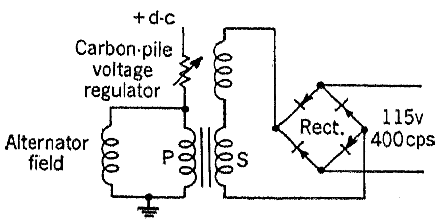


FIG. 12·31.—Schematic diagram of stabilizing transformer in voltage-regulator circuit of 400-cps aircraft inverter.

The resistance of the carbon pile ranges from 2 to 60 ohms.[1] Its electrical rating is based on the rate of allowable heat dissipation, and is given in watts. The unit often used on aircraft inverters is rated at 35 watts. Smaller inverters, notably the Eclipse 100- and 250-va units, use a smaller regulator rated at 20 watts, while 2500-va inverters use a 75-watt regulator, of the same physical size as the 35-watt

[1] Although the 35-watt carbon-pile regulator can be made to operate over a range of resistance from 2 to 60 ohms, it has been found desirable to use only the range from 2 to 30 ohms, as the high-resistance end of the range has a tendency to be unstable.

unit, but with fins to increase the rate of heat dissipation. For the purpose of using a smaller regulator than would otherwise be possible, the carbon pile can be shunted with a fixed resistor. Such an arrangement increases the range of resistance over which the carbon pile must operate, and care must be taken that the maximum stable range of the pile is not exceeded.[1]

The coil of the carbon-pile regulator usually used in aircraft inverters has a resistance of 185 ohms and a current rating of 115 to 125 ma d-c, which gives a voltage drop of 21 to 23 volts. As the voltage to be regulated is 115 volts a-c, rectification and voltage-dropping are necessary. Rectification is provided by a selenium dry-disk rectifier, in series with a "globar" resistor which provides some temperature compensation. The voltage is reduced either by a small autotransformer or by a dropping resistor.[2] In any case, a variable resistor is used, either on the a-c or d-c side of the rectifier, to provide a voltage adjustment whose range is approximately 10 volts.

Figure 12·32 shows a carbon-pile regulator for use with a 10-kva, 3-phase, 208-volt engine generator; Fig. 12·33 is a schematic diagram of the circuit. Note the two potential transformers, connected in open delta, which energize the regulating coil so that the regulated voltage is an average of the three line-to-line voltages. Note also the antihunt circuit and coils on the solenoid.

It is probable that further development of the carbon-pile regulator can greatly extend the usefulness of the device. At the close of World War II, Leland Electric Company of Dayton, Ohio, had developed experimental models of improved carbon-pile regulators that appeared to have a greatly extended operating range of resistance and improved resistance to humidity as compared to service models.

Static Voltage Regulators.—Since the initial emphasis in the design of airborne generating equipment has been on lightness and compactness, and since most of the recent development work on generating equipment has been done in that field, the carbon-pile regulator has received most of the attention and other types have been relatively little developed. The inherent sensitivity of mechanical regulators to shock and vibration and the other shortcomings of this class, together with the increasing importance of electronic equipment with its vulnerability to "jitter" in the power supply, have made the use of static (nonmechanical) voltage regulators more attractive in spite of their greater complexity and weight.

A number of static voltage regulators have been proposed and a few

[1] W. G. Nield, "Carbon-pile Regulators for Aircraft," *Transactions AIEE*, **63**, 839–842 (Nov., 1944).

[2] A third method, employed on the 1500-va series PE-218 inverters as well as a number of others, is the use of a low-voltage tap on the armature winding.

have been built, using various nonlinear circuit elements as sampling or comparison elements for voltage regulation. One type that was tested

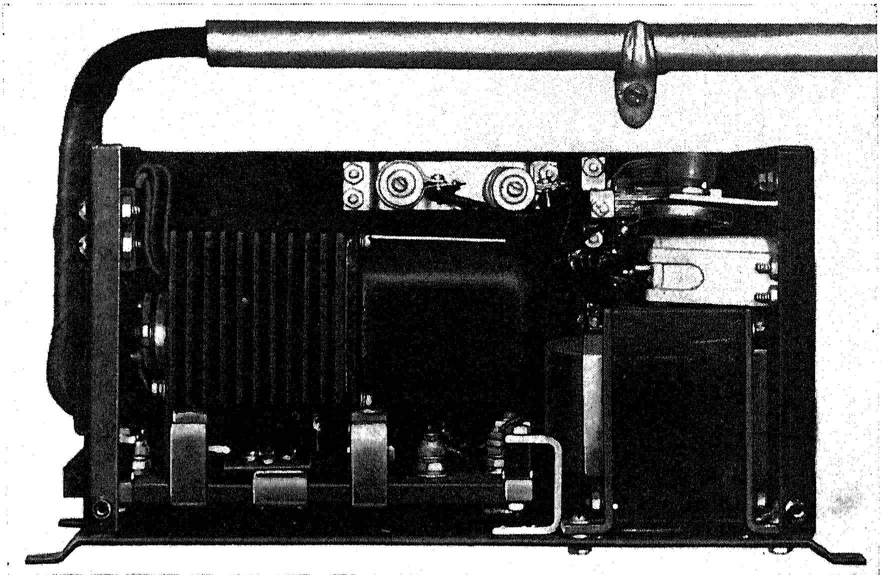


FIG. 12·32.—General Electric Company voltage regulator for 10-kva alternator.

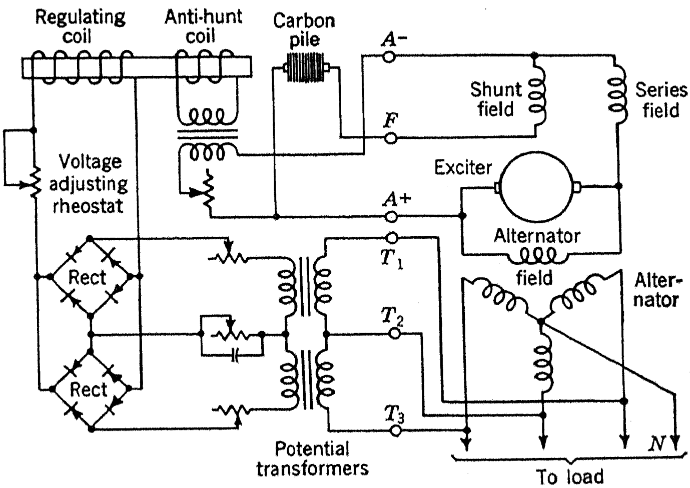


FIG. 12·33.—Schematic diagram of a General Electric Company voltage regulator type GEA-2-B2 and 3-phase 230-volt alternator with exciter.

at the Radiation Laboratory used a saturable reactor as the nonlinear element and controlled the output voltage of an alternator to within 1 per cent when the alternator was driven at constant speed. Such a

regulator might not be applicable to cases in which the alternator speed control is not reliable since the characteristics of the saturable reactor vary with frequency. With adequate frequency control such a regulator seems to have possibilities. Saturable-transformer line-voltage regulators will be discussed in Sec. 12·13.

The most promising static voltage regulators at the present time are the electronic types, of which several different models have been produced. They have suffered in the past from the common misapprehension as to the fragility of electronic equipment, which has been abundantly disproved by the performance of such equipment in military service, and their use will undoubtedly expand greatly in the future.

Electronic Voltage Regulators.—An electronic voltage regulator consists of a voltage-sensitive element, an amplifier, and an output stage which supplies d-c excitation for the generator or alternator field.

Three types of voltage-sensitive elements have been used in experimental regulators. One consisted of a VR-tube bridge excited from a transformer and rectifier connected to the output of the alternator to be controlled. A suitable filter could be added to the rectifier so that regulation was performed with respect to the peak value of the output waveform. Similarly, other types of filters could be used to regulate with respect to the average value of output voltage, or to some chosen value between peak and average. The filter introduces a time constant which, in some cases, is too long to achieve the desired rate of response.

The second voltage-sensitive element, developed by Bell Telephone Laboratories, was a bridge network made of Thermistors and excited from alternating current. This gives an a-c output error voltage that can be readily amplified, but has the disadvantage of a relatively long time constant. The Thermistor bridge, though rather difficult to compensate for wide variations in temperature, regulates to the rms value of output wave, which is a considerable advantage for some applications.

The third form of voltage-sensitive element was a tungsten-filament diode operated in the region of saturated emission. The filament was heated by the a-c output through a transformer, and the anode excited from the d-c power supply. The plate current varies in proportion to nearly the fourth power of the rms value of the alternator output voltage. This provides a very sensitive signal voltage with a very short time constant—that is, if the filament is of small diameter. Such a diode must be ruggedly constructed in order to maintain the mechanical spacing of the tube elements, and thus the tube characteristics, even under severe mechanical vibration.

A conventional d-c amplifier which must have sufficient gain to provide the required over-all sensitivity is used. Stable operation of the combination of voltage-sensitive element, amplifier, output stage, and

alternator demands that the usual conditions for stability of a servo system be fulfilled.

D-c excitation for the alternator field is provided by a controlled rectifier fed from the alternator output. This may have a combination of transformer and rectifier controlled by a saturable reactor, or may use grid-controlled thyratrons for rectification.

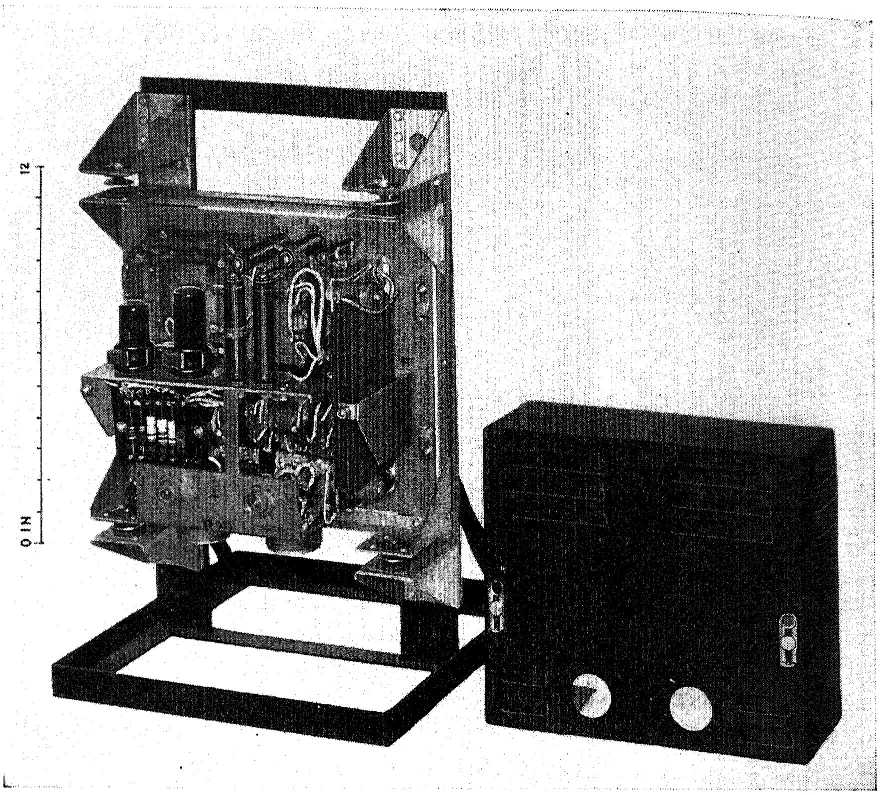


FIG. 12·34.—KS-15055 electronic voltage regulator designed by Bell Telephone Laboratories.

Bell Telephone Laboratories developed a regulated exciter, Type KS-15055, which weighed about 12 lb complete and was meant for use with the PE-218 inverter (see Fig. 12·34). It regulated 115-volts output to about $\pm$ 0.5 volt rms, but had a rather slow response and only fair temperature compensation. The temperature compensation was improved in a later model.

General Electric Company developed a similar regulator, Type 3GVA10BY1, for use with PE-218-D inverters; it used a saturated-diode voltage-sensitive element (see Fig. 12·35). This regulated the 115-volts

output to about ± 0.1 volt rms and had good response and temperature characteristics, but the diode was sensitive to vibration.

In the latter part of 1944, more interest was shown in the development of electronic regulators because of a trend toward the use of engine-driven alternators that were too large for control by carbon-pile regulators unless separate exciter generators were used. The ATSC Equipment Division at Wright Field sponsored the development of two regulators to control and excite engine-driven alternators rated 8 kva, 1-phase, 400 to 800 cps, 115 volts a-c. The weight of these regulators was in the range of 30 to 50 lb, and their operation was reported to be very satisfactory.

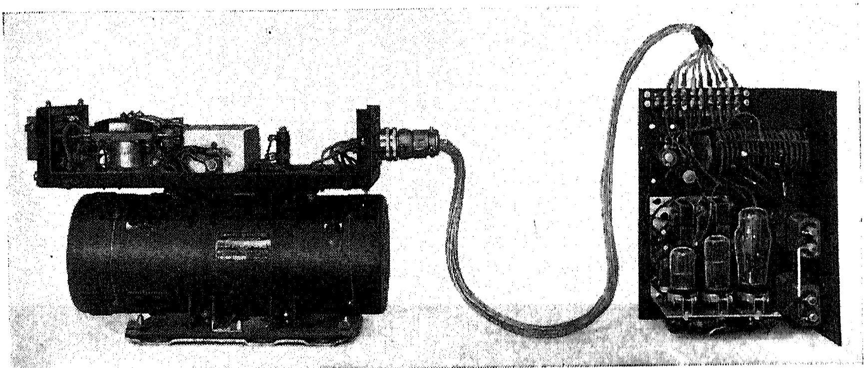


FIG. 12·35.—General Electric Company 150-va aircraft inverter type PE-218-D, 115 volts, 400 cps, and electronic voltage regulator.

In 1945 Radiation Laboratory undertook the development of regulators using a saturated-diode voltage-sensitive element and grid-controlled thyratrons in the output. The intention was to perfect a more or less universal regulator that could be applied to different alternators by changing the thyratron output. The development had progressed to the preliminary test-model stage for two types; one type for single-phase inverters which had been applied to the PU-7 2.5-kva machine, and one type for 3-phase engine-driven alternators of 6.5- to 12-kva rating. The results were promising, and it appears certain that satisfactory electronic regulators can be developed for stationary ground generating equipment as well as for airborne equipment.

12·13. Line-voltage Regulators.—There are many cases in which voltage regulation is necessary but generator-voltage control is impracticable. In such cases it is necessary to use line-voltage regulators. Probably the most common application of line-voltage regulators is the stabilization of the voltage of commercial a-c power lines to improve the performance of electronic equipment. In this section several forms of voltage regulators for both alternating and direct current will be discussed

briefly; a much fuller discussion of voltage and current regulation will be found in Vol. 21 of the Radiation Laboratory Series.

Electromechanical Regulators.—The oldest example of voltage or current regulation is the use of a manually operated rheostat in series with the load; a more modern analogue of the same device is the Variac of the General Radio Company, which has come to be a practically indispensable device in all electrical and electronic laboratory work. Manual control is satisfactory in many cases, particularly where the control requirements are not particularly stringent and the line-voltage variations are comparatively slow. For more critical cases some type of automatic control is necessary. This may take an electromechanical form; a voltage relay across the output line could control a reversing motor that would turn the shaft of the rheostat or Variac in such a direction as to correct the change in output voltage. Such relay-motor-induction regulator devices are often used for voltage control on commercial power lines. Instead of a relay an electronic servo circuit may be used to control the motor; an example of such an electromechanical regulator is the Seco Automatic voltage regulator. This device is made by the Superior Electric Company of Bristol, Conn., in capacities of from 1 to 100 kva. It uses a thyratron control circuit to control a reversible 2-phase motor that drives the shaft of one or more Powerstat variable autotransformers. Its principal advantages are good output waveform, low maintenance, high efficiency, and independence of the output voltage of fluctuations in the load, load power factor, or input voltage. Its principal disadvantage is its slow response, the standard speed being 6 sec from full buck to full boost. This speed is much slower than static regulators but is about ten times as fast as the usual commercial induction regulator and can be somewhat increased if necessary.

Saturable-transformer Regulators.—The most common form of automatic a-c line-voltage regulator is the saturable-transformer type, which is made by Raytheon Manufacturing Company, General Electric Company, and Sola Electric Company. The actual transformer design and circuit details vary with the maker, but the basic theory is the same for all three.

The saturable-transformer voltage regulator may be considered to be a combination of a quarter-wave impedance transformer and a saturating circuit element. The impedance transformer makes the line look like a constant-current source and the saturable element absorbs changes in current due either to line-voltage changes or to load changes. In the simplified circuit shown in Fig. 12·36, if the impedance of the elements to the right of the dotted line is denoted by Z, the voltage across the load e_z will be

$$e_z = Zi_z = e\,\frac{ZX_C}{ZX_C + X_L(Z + X_C)}.$$

At resonance $X_L + X_C = 0$ and the equation reduces to

$$i_z = \frac{e}{X_L},$$

which is independent of the value of Z. The LC-network thus acts as a transformer which forces a constant current through Z when a constant voltage is impressed on the input terminals.

Considering the elements to the right of the dotted line, if the element

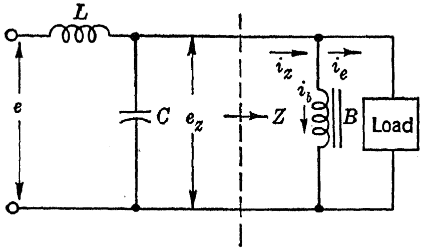


FIG. 12·36.—Simplified equivalent circuit of saturable-transformer voltage regulator.

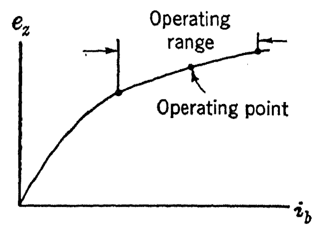


FIG. 12·37.—Voltage-current characteristic of saturable reactor.

B has a saturating characteristic such that over a range of current values the voltage across it varies slowly, as shown in Fig. 12·37, the combination of L, C, and B will act as a constant-voltage source for the load. If the input voltage decreases, the current i_z will decrease in the same propor-

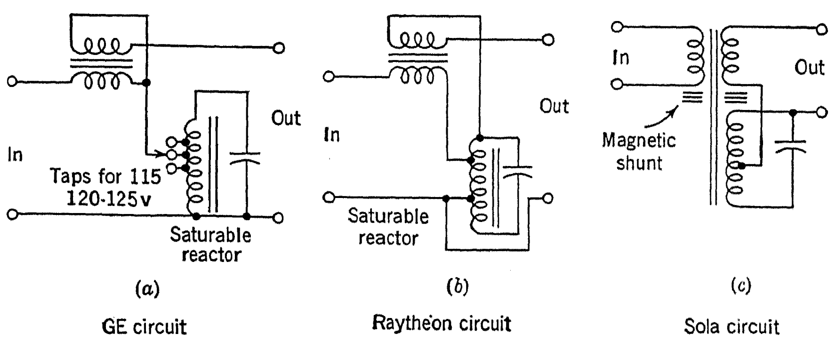


FIG. 12·38.—Commercial constant-voltage transformer circuits.

tion, but if the operating point on the characteristic curve of the saturable element is properly chosen its current i_b will decrease by nearly the same amount as the decrease in i_z, with the result that the load voltage and current will remain nearly constant. Similarly, if the load impedance decreases the load will draw more current, but i_b will decrease by about the same amount and the load voltage will remain nearly constant.

There are several possible types of saturable devices that might be used for the element B, but the most practical one is a saturable reactor.

Such a reactor can be designed to have a fairly flat voltage-vs.-current characteristic over a considerable range of currents, and will give excellent regulation. In the commercial devices the saturable reactor and the inductor L may be combined into a single unit. The actual forms of core and windings differ with the various makers; they are shown schematically in Fig. 12·38.

It is not practicable to design a saturable reactor with a zero slope of the operating range of its characteristic, and commercial constant voltage transformers include a low-voltage secondary winding whose voltage is proportional to the input voltage. This winding is so connected as to oppose the output voltage of the saturable part of the circuit, and the magnitudes of the two output voltages are such that the larger variation of the smaller voltage is equal to the smaller variation of the larger voltage, thus achieving almost complete compensation for input voltage variations. The compensation cannot be complete since the saturation characteristic is always somewhat curved and since changes in load affect the outputs of the two windings differently. Typical regulation curves for a standard 500-va

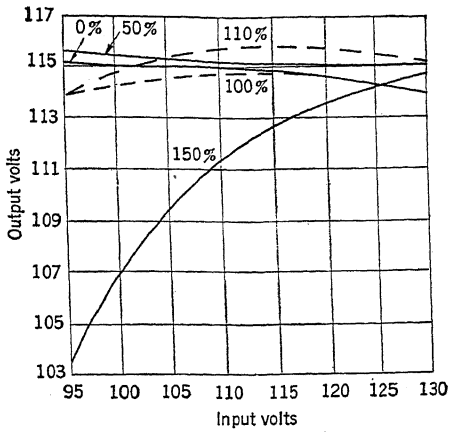


FIG. 12·39.—Regulation curves with resistive load: figures on curves give per cent of full load.

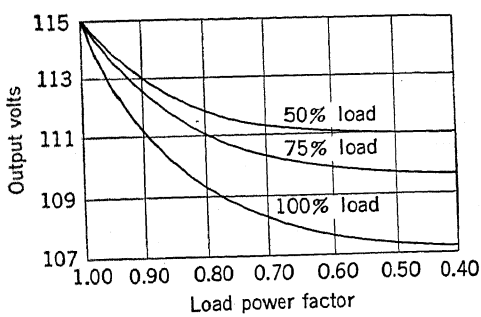


FIG. 12·40.—Effect of load power factor.

unit are shown in Fig. 12·39 for resistive loads. If the load power factor differs from unity the regulation suffers; Fig. 12·40 shows output voltage as a function of load power factor for three different load percentages at standard input voltage.

The outstanding advantages of a saturating-transformer voltage regulator are its rapid response, its simplicity and lack of adjustments,

and its self-protection against overloads. Such a regulator will normally restore the output voltage to its normal value within two cycles after a sudden change of either input voltage or load, which is faster than any other common a-c regulator. The device is inherently simple; it contains no moving parts and no adjustments (except tap-changing switches or jumpers in certain models), and it requires no more maintenance than any other transformer and has as long a life. A most important advantage is its ability to protect both itself and the equipment that it feeds against overloads; even with the output short-circuited the output current will not rise above about 150 to 200 per cent of normal full-load current, and the output voltage will return to normal as soon as the short circuit is removed. Since the rise of input current above normal will be even less, the line fuses will also be protected against blowing in case of a short circuit.

The principal disadvantages of the saturating regulator are its frequency dependence, its poor output waveform, and its stray magnetic field. The usual types of such regulators give constant output voltage at only one frequency, and show an increase of 1.5 to 1.8 per cent of output voltage for 1.0 per cent change of input frequency. This effect is inherent in the operation of the regulating transformer itself, but can be eliminated by adding a suitable series-resonant circuit in series with the output. Such frequency-compensated regulators are available as special-order modifications of the standard models.

The use of a saturated magnetic core involves several effects, of which the most troublesome is the poor output waveform of a typical saturating regulator. The harmonic content of the output voltage varies with both input voltage and load, and varies to a greater degree with small loads and high input voltages. Under the worst conditions it may be 20 per cent or more of the fundamental. The strongest harmonic is the third, which is in such a phase as to give a flat-topped or sway-backed waveform. The crest factor of the output wave is of the order of 1.22, in comparison with the 1.414 of a sine wave. This requires special consideration in the design of rectifiers that are to be fed from such a voltage regulator, and the variation of waveform with varying input voltage and load may lead to variations in the rectifier output voltage even though the rms input voltage to the rectifier may be kept constant by the regulator. The poor output waveform also leads to errors in the indications of certain types of meters; dynamometer- and thermocouple-type meters will read the correct rms values of output voltage or current, but moving-iron types may show waveform errors and rectifier-type instruments will usually read from 8 to 10 per cent high. Care must also be taken in accepting the readings of ordinary ammeters in measuring the load currents of nonlinear loads, particularly if the positive and negative half-

cycles of the load current are different. The regulator must be designed for the maximum instantaneous value of the current in all cases.

The use of a series-resonant output circuit for frequency compensation considerably improves the output waveform, reducing the total harmonic content in a typical case to about 6 per cent at maximum input voltage and 60 per cent load. If still lower harmonic contents are required, regulators may be obtained with special low-pass filters in the output circuit.

The presence of a highly saturated magnetic core in a regulator of this type produces a considerable stray magnetic field with a high harmonic content. Care must be taken, therefore, in mounting a regulator in proximity to equipment operating at low power levels unless this equipment is well shielded. Adequate shielding of the regulator is usually impracticable.

The full-load efficiency of a standard saturable-transformer voltage regulator ranges from about 70 per cent for a 50-va unit to about 95 per cent for a 5-kva unit. For a particular unit the efficiency varies little with input voltage but decreases rapidly with decreasing load. The losses are somewhat higher than those of a standard power transformer of the same rating because of the high core loss in the saturated portion of the magnetic circuit. The total loss and therefore the heating are practically independent of load.

The input power factor of a standard unit at 100 per cent resistive load is fairly high, ranging from 98 per cent leading at minimum input voltage down to 90 per cent leading at maximum input voltage for a 500-va rating.

Regulators such as the Sola, which have electrically isolated output windings, may be operated in multiple. The outputs may be connected in series for higher-voltage operation or in parallel to increase the available output current, but the inputs must not be connected in series. Transformers with electrically connected input and output windings may be operated in parallel, but cannot be operated in series. Two or more regulators may be operated in cascade—that is, with the output of the first feeding the input of the second—and will then give almost perfect compensation of input-voltage variations at some sacrifice of regulation for changing load and of output waveform.

Stock regulators are available in ratings from a few volt-amperes up to 10,000 va, and larger units can be built to order. Some types have tapped windings to permit a choice of nominal 115- or 230-volt input, or to adjust the output voltage. Certain types also have taps that permit operation at either 50 or 60 cps. Most standard units are intended for 60-cps operation but stock designs are on hand for 25-, 50-, and 400-cps units. Available on special order are very small units that are adapted

for incorporation in a-c bridges and other devices requiring 4 to 5 watts of regulated alternating current.

Numerous modifications of standard regulators may be obtained on special order. If the range of input-voltage variation can be decreased the design can be modified so that the output-voltage regulation becomes much better than the standard ± 1 per cent. Conversely, if a greater variation in output voltage can be tolerated the unit can be designed to regulate over a wide range of input voltage; from 40 to 150 volts, for example. Matched and interconnected sets of single-phase regulators can be obtained for polyphase operation. In some types, any reasonable transformation ratio can be furnished besides the usual 1 to 1 and 2 to 1 ratios. This permits drawing regulated 115-volt power from 220- or 440-volt lines, or other similar types of operation. Units are also available in special mountings or housings, such as drip-proof regulators that will withstand the Navy shock tests. Information on these and other special regulators may be obtained from the manufacturers.

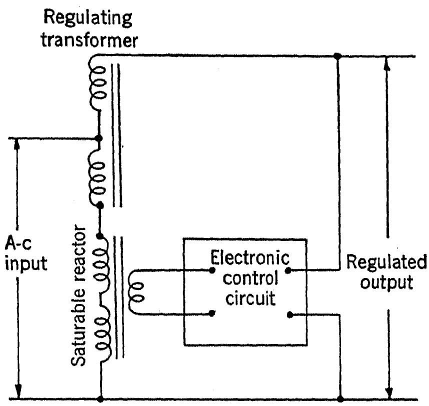


FIG. 12·41.—Basic circuit of electronic line-voltage regulator.

Electronic A-c Line-voltage Regulators.—In an effort to produce a-c line-voltage regulators that would be free from some of the disadvantages of the saturating-transformer type, particularly its frequency sensitivity, considerable developmental work has been done on regulators using electronic circuits. These may be of many different types, but one developed by the Radiation Laboratory is typical. Its basic circuit is shown in Fig. 12·41. The output voltage is equal to the vector sum of the line voltage and the secondary voltage of a regulating autotransformer. The primary of the autotransformer is connected across the line in series with a saturable reactor whose d-c winding is fed from an electronic circuit that is controlled by the output voltage. A vector diagram of the action of this regulator for four different input voltages is shown in Fig. 12·42. In this figure, the input voltages lie along the horizontal axis, V_p and V_s are the primary and secondary voltages of the regulating autotransformer, and V_{sr} is the voltage drop across the saturable reactor. The terminations of the output-voltage vector fall on a circular arc of constant radius with its center at the origin. From the circuit it can be seen that V_p and V_s have a constant ratio and are 180° out of phase and that $V_p + V_{sr} = V_{\text{input}}$, as shown on the vector diagram.

Several different types of sampling and comparison circuits were tried as sources of control voltage for the saturable reactor. One possibility

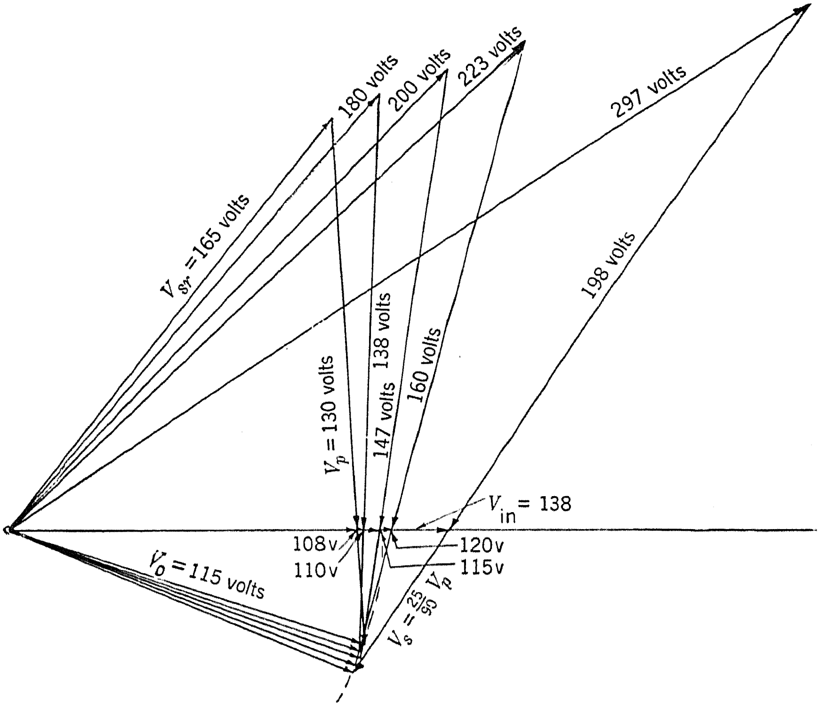


FIG. 12·42.—Fundamental vector diagram of electronic line-voltage regulator.

is to rectify and filter the regulator output voltage and to compare it with the d-c drop across a VR tube. This method works very well but has the disadvantage that it regulates the peak value of the output voltage rather than the rms value. This is unsatisfactory because of the variation of output waveform due to the varying degrees of saturation of the reactor. Thermistor bridges were tried, and gave good rms regulation but were much too sluggish for many applications. The most successful circuit used a voltage-saturated diode, as shown in Fig. 12·43.

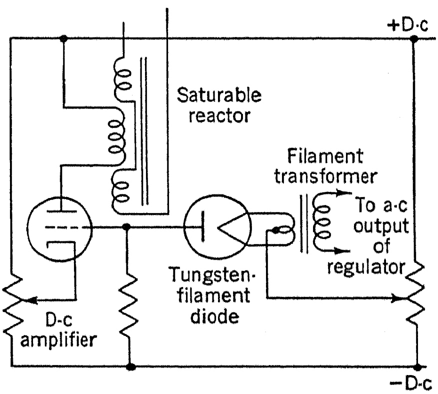


FIG. 12·43.—Emission-tube control circuit.

The diode used in the control circuit may be any tube with a pure tungsten filament. Since the emission of such a filament varies with the

fourth power of its absolute temperature, it furnishes a very sensitive indicator of variations in the output voltage. The heating depends on the rms value of the output voltage, which is the quantity that should be stabilized. In order to obtain a sufficiently fast response it is necessary to use a tube with a comparatively thin filament, which leads to difficulty in applications involving excessive shock or vibration conditions, and the design of a quick-heating diode with a sufficiently rugged filament is the principal problem remaining to be solved in connection with this type of regulator. For all applications except those involving excessive vibration, however, it has given excellent service.

The method of design of this type of regulator may be outlined briefly as follows. It is based on two assumptions:

1. The autotransformer has no losses and its primary-to-secondary coupling coefficient is unity. Its primary inductance will be denoted by L_1 and its stepup ratio by k.
2. The saturable reactor acts as a pure inductance with a minimum inductance value $L_c = 0$ and a maximum $L_c = S$.

An approximate theory of the operation of any regulator using a control inductance in the ground connection of a booster autotransformer

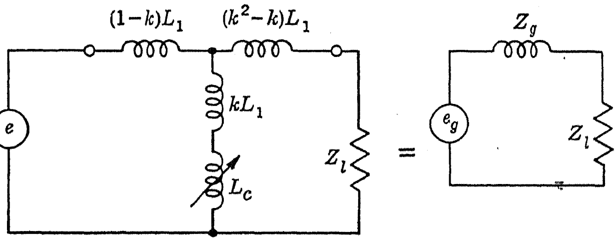


FIG. 12·44.—Equivalent circuit of electronic regulator.

can be derived from the equivalent circuit of Fig. 12·44. As seen from the load, the regulator looks like a generator with an internal impedance of

$$Z_g = j\omega(k-1)^2 \frac{L_1 L_c}{L_1 + L_c} \tag{1}$$

and an open-circuit voltage of

$$e_g = e\frac{kL_1 + L_c}{L_1 + L_c}. \tag{2}$$

If the load impedance is a pure resistance R and the scalar voltage ratio $V_{in}/V_{out} = |e|/|e_l| = q$, where e is the line voltage (taken as the reference vector) and e_l is the regulator output voltage which is to be held constant,

$$q^2 = \frac{R^2(L_1 + L_c)^2 + \omega^2(k-1)^4 L_1^2 L_c^2}{R^2(L_1 k + L_c)^2}. \tag{3}$$

The regulator may be considered as having two modes of operation, depending upon the input voltage. For inputs near the minimum voltage

it acts as a simple booster transformer with a voltage regulation that depends upon L_c. For inputs near the maximum the secondary of the autotransformer acts as a series voltage-dropping choke that is loaded by the control inductor. For intermediate inputs the operation may be considered as including both modes.

When the impedance of the reactor is large compared with that of the transformer secondary the current lags the voltage across the secondary by 90° since its impedance is a pure inductive reactance. If the load is a pure resistance, for which the current and voltage are in phase, the voltages across the load and the secondary must be 90° apart in phase. Since the magnitudes of both the input and the output voltages are known, a vector voltage triangle may be constructed, as in Fig. 12·45. The secondary voltage is tangent to the output voltage locus.

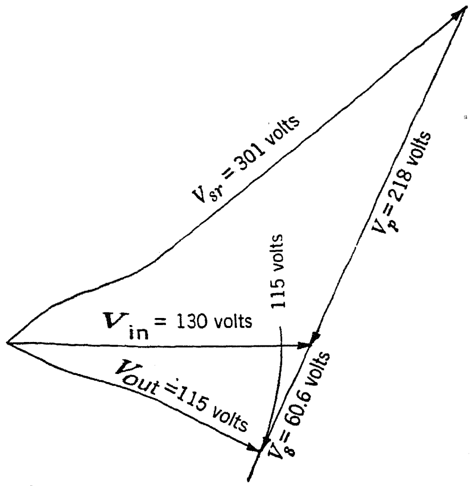


FIG. 12·45.—Vector diagram for maximum input voltage.

Since the primary and secondary voltages are 180° out of phase and have the ratio $V_p/V_s = 1/(k-1)$, the primary vector can be drawn, which establishes the voltage V_{sr} across the saturable reactor, and the diagram is complete.

For the minimum input voltage all voltage vectors are coincident along the reference line and $e_{out} = e_p + e_s$ and $e_{in} = e_p$. For intermediate conditions the calculation is more complicated and depends on the values of R, L_1, and L_c according to Eq. (3). If the load has a reactive component the calculations are still more complicated. Details of the calculations will not be given here, but a vector diagram derived from measurements on a typical electronic regulator of this type is given in Fig. 12·42.

The design of the regulator may proceed by either of two paths, depending upon whether the saturable reactor or the autotransformer is designed first. The maximum values of the voltage drops across the several windings are obtained from the vector diagram of Fig. 12·45; for the condition of maximum input voltage

$$V_s^2 = V_{max}^2 - V_{out}^2,$$

$$V_t = \frac{V_s k}{(k-1)},$$

and

$$V_{sr}^2 = V_{out}^2 + V_t^2,$$

where V_t is the voltage across the whole autotransformer. The maximum current through the secondary will be the load current I_l; the maximum current through the primary and saturable reactor will occur at minimum input voltage and minimum reactor impedance, when $I_{sr} = I_l(k - 1)$.

The minimum primary inductance that the autotransformer may have can be calculated from Eq. (3), using the maximum values of q, R, and L_s, if the reactor is to be designed first. If it is not, a rough calculation of L_1 should be made assuming that L_s is infinite, for which condition

$$L_1^2 = \frac{(q^2 - 1)R^2}{\omega^2(k - 1)^4},$$

where q and R have their maximum values. If ω is variable its minimum value should be taken. For a typical case in which $k = \frac{115}{90} = 1.28$ and $q_{max} = \frac{135}{115} = 1.175$, $\omega L_1 = 7.4R$. This value should be increased to provide a margin of safety; a factor of 2 should be sufficient, but a higher factor does no harm as long as it does not result in excessive size or copper loss in the transformer and reactor. Using this higher factor, for example $\omega L_1 = 15R$ in the case just mentioned, the value of L_c is calculated from Eq. (3), again using the maximum values of q and R.

The design of the saturable reactor depends not only upon the maximum values of current, voltage, and inductance calculated above, but also upon the d-c power that will be available for saturating the core, and this in turn upon the choice of the tube or tubes for the final stage of the d-c control amplifier. A 6L6 or similar tube will furnish adequate power for regulator capacities up to 1 kw or more if the saturable reactor is properly designed, but a filament-type tube is preferable if a minimum warmup time is required. The d-c ampere-turns available should at least equal the maximum a-c ampere-turns and should preferably be somewhat greater.

Having established the design of the saturable reactor the required minimum value of L_1 may be recalculated using the value of L_c from the reactor design. This step, however, is hardly justified in view of the approximate nature of saturable-reactor design and of the design assumptions made in the beginning and also in view of the fact that the action of the control amplifier is such as to compensate for variations in the characteristics of all elements in the circuit. The only effect of a considerable variation in any of the parameters will be an increase or decrease of the operating range or a slight change in the slope of the regulation curve. Further approximations are necessary only when one or more of the circuit elements comes out absurdly large or when weight and size must be decreased as much as possible.

Like the saturable-transformer voltage regulator previously discussed, the electronic voltage regulator furnishes a distorted output wave because of the presence of the saturated-core element. In the latter case, however, the distortion is of such a nature as to produce a peaked instead of a flattened waveform. Appreciable improvement in waveform can be obtained by connecting a resistor across the saturable reactor. Figure 12·46 shows typical uncorrected and corrected waveforms, with a sine wave for comparison. The addition of the correcting resistor lowers the efficiency and increases the minimum permissible value of I_L. It should be made adjustable so that the optimum waveform can be secured at the normal value of load. Waveform correction is most desirable for 60-cps operation. The waveform of the usual small generator operating at 400 cps or above is likely to be so bad that any regulator will normally improve it.

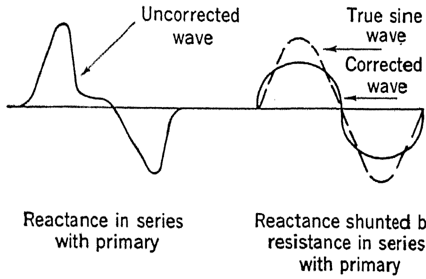


FIG. 12·46.—Waveform corrections in voltage stabilizer.

The frequency range of an electronic voltage regulator of this type depends principally on the design of the saturable reactor. If the power for the control amplifier is taken from the output circuit, as is usually the case, a saturable-reactor impedance that is too high or too low will result in an excessively low or high voltage to the amplifier power supply during the warmup period, especially if the line voltage error is in such a direction as to exaggerate the condition. If necessary a single-pole double-throw time-delay relay can be added to permit the amplifier to be warmed up from the input voltage and then switched to the output for normal operation. If no special precautions are taken in the design of the magnetic circuits a ± 20 per cent change in operating frequency can be tolerated, the only effect being a small change in the regulating range.

The size and weight of an electronic regulator of the type described depend on the allowable operating temperature of the coils, the power output, and the type of mounting and weatherproofing used. A laboratory model of a 350-watt 400-cps regulator that proved successful in field service weighed $12\frac{1}{2}$ lb and had a volume of 330 in.³ The 1700-watt 60-cps version of this model weighed about 100 lb. The weights of the commercial versions run from 28 lb for the 250-watt model to 160 lb for the 5-kw model.

The performance of a typical commercial version of the regulator just described is very good. The output voltage is adjustable from 110 to 120 volts and will maintain that value within 0.2 per cent for input

voltages from 95 to 130 volts and frequency variations of ± 15 per cent. It is alleged to be independent of load power factor, though this may be doubted for loads of very low leading power factors for which resonance might occur. It has a quick response time, 6 cycles maximum. Four standard models are available from Sorensen and Company, with outputs of 250, 1000, 1750, and 5000 va, plus a light ($16\frac{1}{2}$-lb) model for 400-cps airborne use. A somewhat similar regulator using a carbon pile instead of the electronic amplifier for controlling the saturable reactor is made by the Aircraft Equipment Manufacturing Company of Dayton, Ohio.

D-c Line Voltage Regulation.—The problem of regulating the voltage of a d-c line occurs relatively infrequently since most direct current used in electronic equipment is either regulated at the generator, as described in Sec. 12·12, or is derived from a-c lines via transformer-rectifier-filter power supplies that may or may not be regulated. If regulation is used the regulator is normally considered to be a part of the power supply, but there is no logical reason for this and it is occasionally desirable to regulate the voltage of a d-c line remotely from the source of power.

Basically there are three methods of regulating the voltage of a d-c line.

1. A variable series element, normally a vacuum tube, may be used as a dropping resistor.
2. A variable shunt resistor, also usually a tube, may be used to pull down the voltage of a line with poor regulation. If the regulation of the line is too good a series resistor can be added.
3. An additional source of d-c power can be added in series with the line, either aiding or opposing the line voltage. This method is seldom used.

Methods 1 and 2 can only act to reduce the line voltage and not to increase it. The choice between Methods 1 and 2 depends upon the application; the first method is more common and is indicated in cases of low voltage and relatively high line current. The second method is used principally for the regulation of high-voltage low-current sources such as are used for such applications as CRT high-voltage supplies, etc. Details of d-c regulators will not be given here; they are thoroughly discussed in Vol. 21 of this series. Commercial regulated power supplies are available from a number of manufacturers, and many papers on the subject have appeared in scientific and engineering journals over the last ten years.

CHAPTER 13

RELAYS AND RELATED DEVICES[1]

BY J. F. BLACKBURN

A relay is an electrically operated switch, and the two basic criteria in selecting a relay for a particular purpose are first, the switching operation that is to be performed, and second, the power source that is available to actuate the relay. The one determines the number, type, and arrangement of the contacts required; the other, the design of the coil and the magnetic circuit. There are, of course, many auxiliary specifications to be satisfied, such as size and weight, expected operating life, liability to failure and the severity of its consequences, insulation, resistance to shock and vibration, etc. These will be taken up in the latter part of this chapter, after discussing the contacts and the coil and magnetic circuit.

In the interest of brevity, the discussion will be confined to low-power relays of the type usually used in electronic equipment, omitting the larger types used primarily in industrial equipment and mentioning only briefly a few relays of special construction or function.

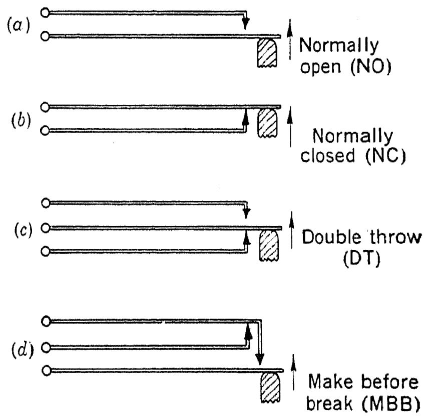


FIG. 13·1.—Basic relay-contact groups.

13·1. Contacts.[2] *Contact Arrangements.*—The general arrangement of the contacts of a relay is determined by the number and sequence of the switching operations to be performed. Relays are available in many forms, with contact arrangements ranging from a single pair, to make or break a single circuit, to stacks of dozens of contacts handling a number of independent circuits. For most purposes, however, there are four basic contact groups, as shown in Fig. 13·1. Practically all relay contact arrangements can be

[1] There is an extensive literature on relays, but books devoted specifically to relays of the class discussed here are rather rare. One of the most recent is *Relay Engineering*, by Charles A. Packard, Struthers-Dunn, Inc., Philadelphia, 1945.

[2] See Packard, *op. cit.*, pp. 75–101; also G. Windred, *Electrical Contacts*, Macmillan, London, 1940.

considered as made up of one or more groups of these four types. Figures 13·1*a* and *b* are self-explanatory; *c* and *d* differ only in that with *c* the circuit from one to two is broken before that from one to three is established, while the opposite is true with *d*. Double-break, DB, contacts imply the use of two contact groups, usually *a* or *b*, in series.

In an assembly of several contact groups some control of the sequence of contact-making can be obtained by adjusting the individual contacts;

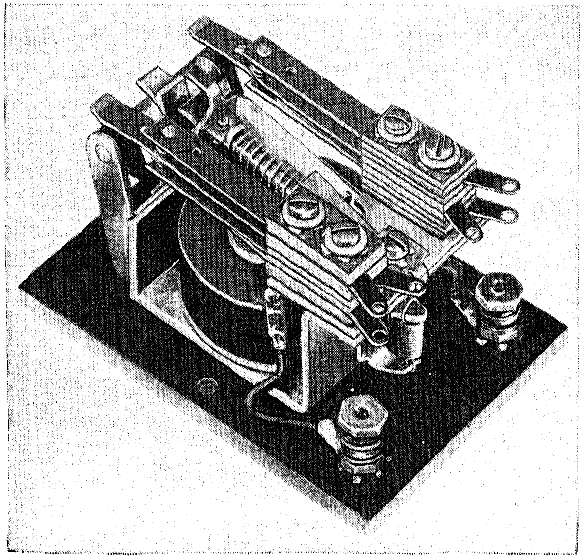


FIG. 13·2.—Advance Electric Company type 904A indexing relay.

for example, in a double-pole single-throw, DPST, relay, if one fixed contact is set somewhat ahead of the other it will make first, and will break last when the relay is deenergized. In general, however, if the sequence and timing of switching operations are important it is best to use a relay in which the several contact groups are operated by individual cams, as in relay No. 91 Table 13·5 (Fig. 13·2) or to use several relays in cascade, each relay after the first being energized through contacts on an earlier one in the series.

Contact Ratings.—Having established the contact arrangement, the contact size and materials must be chosen in accordance with the electrical characteristics of the circuits to be made or broken. Here there are three operations to be performed; the circuit must be established when the contacts close, it must be maintained as long as they are held together, and it must be broken when they separate.

Successful establishment of the circuit demands that the contacts close cleanly with minimum bounce or chatter, and that they are suffi-

ciently large, of the correct material, and actuated with sufficient force to prevent welding or arcing with the initial value of the current. Certain types of loads, especially motors, tungsten-filament lamps, some heaters, and circuits in which there is a considerable amount of energy stored in condensers, have a high inrush current that later drops to a much lower value. In the case of motor and lamp loads, this inrush current may be 5 to 12 times the steady value. In such cases the inrush rather than the steady current determines the choice of contacts.

Successful maintenance of the circuit once it is established demands that the contacts be large enough, properly shaped, clean and smooth enough, and adequately held together so that the contact resistance is sufficiently low to carry the steady current without excessive heating or voltage drop. In very low-voltage circuits the contact resistance may be an important factor, and special precautions may have to be taken to keep the contacts clean and smooth, and to prevent even slight momentary opening due to shock or vibration.

Successful interruption of the circuit demands that the contacts open cleanly and rapidly to a sufficient distance to extinguish the arc that always forms on breaking a circuit. High speed of separation without momentary reestablishment of the circuit, wide separation of the opened contacts, and the use of several gaps in series permit the interruption of larger currents. High voltage, low atmospheric pressure (as in high-altitude airborne operation), excessive arc-forming tendency of the metal of the contacts, and particularly highly inductive loads greatly decrease the interrupting capacity. In many cases it is necessary to use auxiliary arc-suppressing devices, such as blowout coils in series or RC-circuits in shunt with the gap. Blowout coils find considerable use in the field of power relays, but are seldom applied to small units because of insufficient space and the tendency of the drawn-out arc to strike other closely adjacent contact groups. Arc-suppressing circuits are discussed in Sec. 13·3.

Careful perusal of a number of relay catalogs indicates that there is no general agreement on the amount of current that can be safely handled by a given pair of contacts, but by plotting contact diameter, etc., against ratings and by referring to the few definite statements made by the manufacturers, some rough rules can be laid down. Silver contacts used in the low-power relays discussed here are good for currents up to about 3 or 4 amp in the $\frac{1}{8}$-in. size, 5 or 6 amp in the $\frac{3}{16}$-in. size, 8 or 10 amp in the $\frac{1}{4}$-in. size, and 15 or 20 amp in the $\frac{3}{8}$-in. size. These values apply to at least 90 per cent of the several hundred relays checked. They may be too conservative, since several reputable relay manufacturers use higher ratings. Double-break contacts will handle about 50 per cent more current than single-break. These ratings are for 115-volt 60-cps a-c, or for d-c voltages up to 32 volts, and for noninductive loads

without excessive inrush currents. They are about half the value of current which can be handled without appreciable heating by a pair of contacts with the usual contact pressure of 1 to 2 oz. For 110 volts d-c the current ratings should be halved. Increased contact pressures somewhat increase the ratings, especially for large contacts. For very low voltages, contact heating is the only limitation and ratings may be doubled. Quick-break operation and wide contact separation permit some increase in current rating, especially at higher voltages and with inductive loads.

For contact materials other than silver, palladium will carry two or three times the current at the same voltages. Platinum-iridium has about the same current-carrying capacity as palladium, but its great hardness gives a much longer contact life under severe mechanical operating conditions. Tungsten contacts will handle only about 75 to 100 per cent of the current of silver contacts of the same diameter, but will do so at two or three times the voltage.

The ideal contact material should have high electrical and thermal conductivity, high melting and vaporization temperatures, and high resistance to mechanical wear. In addition, the ideal contact material should have either no tendency to form an oxide or tarnish film, or at least such a film should be of low resistance. High thermal conductivity aids in carrying heat away from the point of contact. A high melting point improves the ability of the contact to withstand high arc temperatures without melting or welding the contacts. High vaporization temperature results in less tendency for the formation of metallic vapors that help to maintain an arc. High electrical conductivity usually means lower contact resistance and less contact heating, which is especially important where high current densities are employed on the contacts.

High contact pressure is an aid in breaking down any film of dust or oxide that may prevent the contacts from coming together and also improves the ability of the relay to maintain contact during shock and vibration. Some relays have adjustable armature springs that permit some adjustment of contact pressures.

Contact follow-through is the motion that occurs after the physical contact has been made. Contacts mounted on leaf-type springs must have follow-through to deflect the springs and build up the contact pressure. During the follow-through the contacts slide over one another with a wiping action that aids in keeping the surfaces clean.

Low-voltage contacts are particularly susceptible to failures because the voltage may not be sufficient to break down any nonconducting film or dust between contacts. Where hermetic sealing is not possible it is desirable to mount relays with the contacts in a vertical plane to minimize the tendency for dust to accumulate.

The contact gap must be sufficiently wide to extinguish the arc that forms on opening the contacts and to withstand the maximum voltage that is to be impressed across the gap. As in the case of contact diameter, a study of the relation between gap and ratings shows very little correlation between the two; apparently a gap of 0.010 in. or less is good only up to about 1 amp; 0.010 in. to 0.025 in. up to 15 amp. Currents of 20 amp or more usually require two gaps in series.

It is incorrect to assume that twice the current can be carried by connecting two sets of contacts in parallel; it is impossible to ensure simultaneous opening and closing of the two sets, and the make and break will be handled by only one set.

Double-break contacts are more effective in arc interruption than single breaks of the same total contact separation.

High speed of contact operation is desirable because it reduces the duration of the arc and thereby decreases the heating of the contacts.

Most relay contacts rebound and reopen their contacts once or several times during the process of closing, and many do so also on opening. This is an objectionable feature but is difficult to overcome, particularly where the contacts are of the butt type. Contact bounce is particularly destructive when there is a high inrush current, since the contacts are reopening at a time when the current may be several times its full-load value. Contact bounce reduces contact life and may cause fusing of contacts.

From the standpoint of high current-carrying capacity the ideal contact shapes are two flat-faced surfaces, which provide the largest possible contact area for a given contact size. The objection to this construction is that it is almost impossible to maintain perfect alignment of the contacts and it also provides less unit pressure between contacts, which reduces the effectiveness of pressure breakdown of any nonconducting film. For this reason most relay contacts have at least one radius-faced surface per pair.

Actual measurements on a large number of small relays as delivered showed practically no correlation between contact pressures and current ratings. Actual pressures ranged from zero (where the contacts did not even touch) to about 1 lb. The average pressure for most types of relays was from 1 to 2 oz. One manufacturer of telephone-type relays uses a standard pressure of 30 to 40 g, increasing this to 70 g in relays intended for use under conditions of vibration, and reducing it to not less than 15 g for certain special applications. High-current relays such as aircraft motor contactors use from 1 to 2 lb.

The variability in contact pressures and gaps perhaps illustrates as well as anything the considerable variability in the properties of commercial relays. Both quantities can be adjusted on almost any relay by

a careful and skilled technician, but manufacturing tolerances and the unskilled and sometimes careless assembly practices necessitated by manufacturing to meet low-priced competition result in great variations in contact settings. For critical applications all relays should be checked and adjusted individually before installation; but such adjustment should not be attempted unless the adjuster thoroughly understands what he is trying to do. If it must be done, it is most desirable to ascertain from the manufacturer the correct settings for the performance desired.

Certain special forms of contacts are sometimes used for especially severe operating conditions. For cases in which the coil voltage fluctuates through the range within which the contact pressures are insufficient to maintain proper contact, whether from vibration or other causes, snap-action switches such as microswitches are often used. For high-voltage operation, especially at radio frequencies and at high altitudes, vacuum contacts are frequently the only solution. Both vacuum and mercury contacts are useful for operation in explosive atmospheres. Relays using such forms of contacts, however, are usually bulkier and more sluggish in operation than the ordinary types, and are not often manufactured in contact arrangements more complicated than DPDT. Mercury contacts are especially vulnerable to disturbances from vibration and shock and must be mounted in a fixed position, which usually rules them out for mobile applications, especially in aircraft.

13·2. Coils and Magnetic Structures.[1]—Having established the contact design, which in effect determines the amount of work to be done by the relay armature, it remains to choose a suitable magnetic structure and coil to do that work when energized from the power source to be used. The magnetic structures used in most small relays can be classified into four principal types, shown in Fig. 13·3. Numerous variations exist in the mechanical assembly, arrangement, and composition of various parts of the many relays that are available.

Magnetic Circuit.—Figure 13·3*a* shows the magnetic circuit of a common type of single-coil clapper-armature relay. (Contacts, mounting details, armature restoring spring, etc., are omitted from all the views in Fig. 13·3.) The useful magnetic flux that actuates the armature is the flux in the air gap between the armature and the pole face. The flux must also traverse another gap at the hinge end of the armature, but the flux passing through this gap does not contribute to the pull on the armature. The magnetic reluctance of the air gap at the hinge is sometimes reduced by providing fins of magnetic material on the armature.

[1] See Packard, *op. cit.*, pp. 373–416, for a discussion of relay coils and magnetic circuits. A very thorough discussion of design methods is given in H. C. Roters, *Electromagnetic Devices*, Wiley, New York, 1941.

Figure 13·3*b* shows the magnetic circuit of a double-coil relay. With this construction the flux again traverses two air gaps, but the flux in each gap now contributes to the pull on the armature. Relays using two-coil construction can therefore be designed to operate on fewer ampere-turns than the previous type.

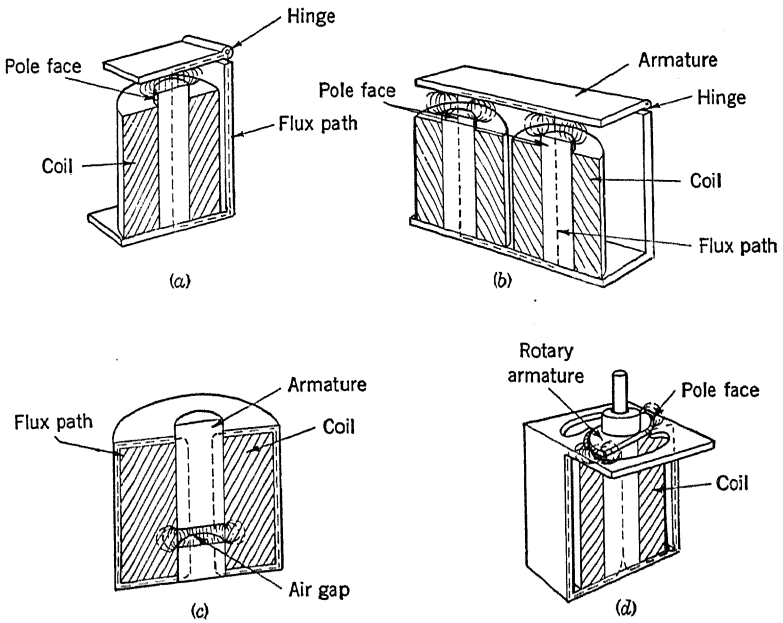


FIG. 13·3.—Basic relay magnetic structures. (*a*) Single-coil clapper type; (*b*) two-coil clapper type; (*c*) plunger type; (*d*) rotary type.

Figure 13·3*c* shows a solenoid or plunger-type structure providing a comparatively large armature pull in a compact size. This construction is widely used for aircraft contactors with contacts carrying as high as 200 amp at 30 volts direct current.

Figure 13·3*d* shows a rotary-type armature construction. Although not many relays of this type are available, its symmetry should make it more vibration- and shock-resistant than most other types.

In good magnetic-circuit design the leakage flux, that does not traverse the armature-to-pole-face air gap, is reduced to a minimum. Designs with short chunky coils and low-reluctance paths except for the useful air gap usually have low leakage; long-coil telephone-type relays in which the return path hugs the outside of the coil are prone to have high leakage, especially when the use of an armature-end slug crowds the coil to the heel end of the core. Such a construction may require up to 25 per cent more ampere-turns than would otherwise be needed.

Alternating-current relays require a shading coil in the pole face to minimize armature chatter and hum. Most small a-c relays do not require laminated cores to limit eddy-current heating because the cross section of the core is small, but the best designs do use laminations.

Since the cheaper magnetic materials have considerable residual magnetism most d-c relays, especially the power-sensitive types, require an appreciable minimum air gap to prevent the armature from sticking to the pole face when the coil current is reduced to zero. In many relays this is obtained by spot-welding a nonmagnetic shim to the pole face or to the armature, but some types use a nonmagnetic screw in the armature opposite the pole face to permit adjustment of the residual gap. The effect of residual magnetism may often be countered by using a stronger armature return spring, but this requires an increase of power of the coil. For high-sensitivity relays where the air gap must be kept to a minimum it is necessary to use materials such as permalloy which have very low residual magnetism. Such materials also have high permeabilities that help to increase the efficiency of the relay.

Coil Construction.—Methods of winding, insulating, and impregnating relay coils will not be discussed here since the discussion would largely duplicate that given in Chap. 4 of this volume. The method of construction is important, however, since it largely determines the maximum safe operating temperature of the winding, and this in turn governs the coil wattage and the maximum force available at the armature. If there is no limitation on the size and weight of a relay there is theoretically no limit to the power sensitivity that can be attained. By increasing the area of the flux path while maintaining the ampere-turns and coil wattage constant the total air-gap flux and therefore the armature pull can be increased indefinitely, and the increased coil area will permit cooler operation of the coil. In practice, however, in addition to the increased space, weight, and cost, the armature would become so massive and the coil inductance so high that the relay action would become very sluggish due to the combined mechanical and electrical inertia. It is more practical to build a relay of reasonable size and, if necessary, to amplify the controlling power either with vacuum tubes or by the use of a small high-sensitivity pilot relay.

Maximum Operating Temperature.—The maximum continuous power input to a given relay coil is limited only by the maximum temperature that the coil insulation can withstand without breakdown during the required life of the relay. This temperature is dependent on the coil construction, the nature of the insulating material, and the conditions of operation. If the coil is operated in intermittent duty, where it is never excited for a long enough period to attain the high temperature that it would reach with continuous excitation, the most important criterion is

the thermal capacity of the winding and any adjacent parts that are in good thermal contact with it.

In deciding upon the maximum operating temperature a number of factors must be considered. Since insulation breakdown is a progressive process a relay in an expendable device such as a bomb could be allowed to run at a temperature that would cause charring and breakdown in a few minutes; on the other hand, a relay for an industrial control application or one used in an unattended device such as an automatic lighthouse or weather transmitter would have to run at a low power input to avoid eventual failure. Under humid conditions a high but not excessive temperature might be a virtue since it would help to dry out the coil, though in such a case there would always be the danger of electrolytic corrosion of the winding. In general, except with the newer high-temperature insulations, the maximum temperature is in the neighborhood of 220°F; one manufacturer specifies this for enameled-wire windings and 250°F for silk-covered wire.

The maximum temperature depends upon the power input, the ambient temperature, and the method of cooling. For usual ambient temperatures the same manufacturer allows 2 watts/in.^{2} of coil radiating surface (excluding the coil ends) for enameled wire and $3\frac{1}{2}$ watts/in.^{2} for silk; if the relay is enclosed these values are reduced to 1 and $1\frac{1}{2}$ watts. In combat and other equipment where considerable power is being dissipated in a small volume the ambient temperatures will be very much higher than is usual in laboratory or in most commercial practice, and in such cases a considerable reduction in coil power may be necessary. In the relay tests reported later in this chapter an ambient temperature of 65°C was chosen; this represents a high but not extreme temperature for combat equipment. Of the hundred or so relays tested only about one third did not exceed 100°C under the conditions of the test, and many of these were power-sensitive types for which heating is seldom a consideration. Besides starting from a high ambient temperature, the coils were overvolted 25 per cent in most cases, making the test doubly severe; so these results should not be taken to mean that the average relay is likely to burn up under average conditions. Alternating-current relays usually run somewhat hotter than d-c relays of the same types, not only because they are less power-sensitive but also because when alternating current is used, eddy-current and hysteretic heating help to raise the temperature.

One effect of coil heating that is often overlooked in relay applications is the increase of coil resistance associated with increasing coil temperature. At 25°C copper wire increases in resistance about 0.4 per cent per degree centigrade. In many cases the high temperatures attained in service may cause a 30 to 40 per cent increase in coil resistance, and the decreased power drawn from a constant-voltage source may cause poor

operation of the relay. When the coil is powered from a constant-current source such as the plate of a vacuum tube this effect is usually negligible. In vacuum-tube applications, however, if the plate current contains considerable ripple, as is the case with rectified but unfiltered current, the a-c component may cause appreciable heating without contributing to the armature pull, so that the dissipation should not be considered to be merely that of the I^2R loss due to the d-c component alone.

Power Requirements.—The actual power required to operate small relays of the types described here varies from a few milliwatts to a few watts. In classifying the relays whose tests are outlined in Sec. 13·7, those with an actual minimum operating power of less than 100 mw were classified as "sensitive" and listed in Table 13·2; they required from 6.4 to 90 mw. Two of the "special" relays in Table 13·5 were also sensitive; the Allied Control Company Type CS balanced relay (No 93) operated on 59 mw and the Barber-Colman polarized relay (No. 94) on only 0.6 mw. Of the d-c relays listed in Table 13·1, about two-thirds required from 0.1 to 1 watt, one-fourth from 1 to 2 watts, and the rest from 2 to 3 watts. These are minimum values, the actual wattages at rated voltage being considerably higher; one third of the d-c relays listed required from 0.1 to 1 watt, one third from 1 to 2 watts, one fourth from 2 to 3 watts, and the others from 3 to 6 watts. These percentages are not particularly significant, but do indicate what may be expected.

Power requirements were not measured for the a-c types, but from data given in several catalogs, a-c relays require from one and one half to four times the wattage of d-c relays of the same construction. This discrepancy is greater the lower the power; d-c relays operating on less than 10 mw are not difficult to make, but 35-mw sensitivity is high for alternating current, and in some cases the sensitivity ratio is as high as 15 to 1.

The power factor and impedance of relays are very sensitive to air-gap adjustment, but for most 60-cps relays the ratio of volt-amperes to watts falls between $1\frac{1}{2}$ and 4. Because of the increase of inductance with the shortening of the air-gap the a-c coil current with the armature closed is usually about 60 per cent of that with it open. The inductance of the usual small 110-volt relay with the armature closed is of the order of a few henrys.

Voltage and Current Variations.—In designing a relay, consideration must be given to the voltage or current variations likely to occur in service. For military use, the expected ranges are from 25 to 30 volts for a "24-volt" d-c source, and from 92 to 138 volts for a nominal 110-volt 60-cps source. Such variations are large but by no means unknown in commercial service. To pass the test a relay must operate satisfactorily on the minimum expected voltage immediately after having

attained the maximum temperatures produced by continuous excitation with the maximum expected voltage. Such a test is admittedly severe, but if the ambient temperature and voltage ranges are fairly chosen for the intended use, a relay that will not pass this test will not be satisfactory. A wide range of supply voltage or current variation requires more coil power at the nominal operating value, and frequently a larger and heavier relay than if the variation were small.

Various other factors affect the coil power requirements to some extent. In the case of sensitive relays an increase in the number of contacts increases the power required; in the case of one particular type the single-pole model operated on 15 mw, but the double-pole required from 60 to 70 mw. This effect is much less apparent for the higher-power relays since they are usually over-powered to ensure fast operation of the relatively heavy armature. Relays for special operating conditions, such as high-inrush-current, close-differential, latching, or indexing relays, usually require twice to four times as much coil power.

In some relays where it is not desirable to provide mechanical locking devices, and where the coil must handle enough power to cause serious overheating if the current remains at its initial value, two windings are sometimes provided. Such relays have a pair of auxiliary normally closed contacts to break the current in the low-resistance winding when the armature closes, while the high-resistance winding furnishes enough flux to hold the armature closed but not to close it. Another method is to use an auxiliary relay that has a pair of normally closed contacts connected across a resistor in series with the coil of the main relay. The auxiliary relay coil may be connected to the same power source as the main relay, in which case it should be a slow-operating type, or it may be powered through a pair of normally open auxiliary contacts on the main relay. The method requires an extra relay and resistor, but avoids the necessity of a special double-winding relay.

Voltage and Current Requirements.—In control applications it is often important to consider the range of input voltages or currents required to operate and to release the relay. Most relays are poorly adapted to applications that require great constancy of pull-in and drop-out currents, particularly if these are to be nearly the same. This is due primarily to two causes; hysteresis in the magnetic circuit, that can be minimized by the use of suitable materials, and the change of reluctance with air gap. As the gap is reduced the total reluctance in the magnetic circuit is also reduced and consequently the magnetic flux and pull on the armature increase rapidly as the armature approaches the pole face. The armature pull in the closed position may be several times the pull in the open position with the same coil current. Since the reluctance has been decreased with the closing of the gap, the coil current can now be reduced

below the operating value before the flux will again drop to a value where the restoring spring overcomes the armature pull and opens the gap. This latter value of current is called the "release current" of the relay; the value necessary to pull the armature in from the open position is called the operate current.

The operate current of a given relay is determined by the length of the open air gap, the rising magnetization current of the iron with the open gap, and the spring-restoring force on the armature. The release current is determined by the length of the closed gap, the falling magnetization curve of the iron with the closed gap, and the spring force. To make the release current approach the operate current the ratio of open-gap to closed-gap lengths must approach unity and the residual magnetism in the iron must be reduced to a minimum. Close-differential relays are therefore much less power-sensitive than the normal type, since the open gap must be made long to maintain near unity ratio between closed- and open-gap lengths. Extremely close differentials, as for generator voltage control, are best obtained by a moving-coil construction, where the air gap and reluctance remain constant.

In ideal relay operation, the pressure on the normally closed contacts remains constant until the coil current reaches a definite value and at this value (the operate current) the movable contacts transfer from the normally closed to the normally open contacts with full pressure immediately applied to them. On release the same operation takes place in reverse order. In actual practice such conditions are not attainable. Usually there is a range of coil currents near the operate and release points where the contact pressure becomes very small and contact continuity becomes erratic, especially under vibration and shock. With good relay design the coil-current range of erratic operation is small.

There are certain methods of avoiding the condition just described, usually at the expense of widening the range between operate and release currents. One is the use of snap-action contacts such as microswitches, and the other is the use of small permanent holding magnets with a high force-to-armature-displacement gradient. Several manufacturers are making relays with microswitch or similar contacts; holding magnets are used principally on high-power relays and contactors, although they have been applied to certain moving-coil voltage relays. Somewhat the same effects can be produced by certain special relay constructions such as are used in high-speed telegraphic keying relays. These usually involve several differentially connected windings and magnetic circuits much more complicated than those of the usual power relay. Incidentally, it was noted during the relay tests described in Sec. 13·7 that relays employing only leaf-type springs usually have more clearly defined operate and release currents than those that employ an additional armature restoring spring.

From the above it can be seen that a careful choice of relays must be made when the coil current varies gradually through the operate and release values. If possible, the circuit should be redesigned to produce a rapid variation. This is particularly true in the a-c case because of the wide range of coil current values at which chattering occurs; a gradually varying low-frequency alternating current is about the worst possible source of relay coil power.

13·3. Operate and Release Time.—Relays vary widely in the time taken to perform their switching operations, and there are a number of methods by which these times can be controlled. In general, high-speed operation is attained with low coil inductance, light moving parts, high power input, short stroke, and magnetic material laminated to reduce eddy currents. The effect of inductance is often large; in a certain telephone relay with an operating time of 12 msec, it requires 10 msec for the current to reach the operate point and only 2 msec for the armature to respond. One possible way of speeding up the response of a d-c relay would be to operate it from a voltage source several times larger than its rated voltage, with a condenser to store enough energy to kick the relay closed and a resistor in series with the power supply to limit the coil current. The principal objection to such a scheme in most cases is the large size of the condenser required. Some special types of fairly sensitive relays have been designed for high-speed operation, but most sensitive relays are somewhat sluggish. Increasing the number of contact springs on a given relay increases the operate time and decreases the release time. The latter is also affected by the manner in which the coil current is interrupted; if an arc persists during the interruption the release time will be longer. Typical operate- and release-time curves are shown in Fig. 13·4.

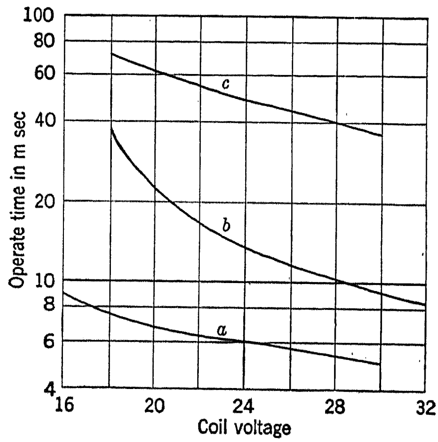


FIG. 13·4.—Typical operate-time curves. (*a*) Potter and Brumfield KLD-1, release time 13 msec; (*b*) Allied BJC6D36, release time 9 and 3 msec for two samples; (*c*) G-M Laboratories 13117, release time 7 msec for each of two samples. (Release times were independent of voltage.)

One way of reducing release time and at the same time eliminating residual magnetic effects is the addition of a small constant magnetomotive force opposing that of the operating winding. This can be furnished either by a small permanent magnet or by an auxiliary winding.

When the circuit to the main winding is interrupted the opposing magneto motive force makes the effective flux decay more rapidly and also cancels the magnetomotive force of residual magnetism.

Exclusive of relays especially designed for high speed, operate times of 5 to 10 msec may be considered fast. Of the relays in Table 13·1, 80 per cent had operating times between 6 and 30 msec. Release times were shorter and more constant, with 80 per cent between 3 and 11 msec. Alternating-current relays operated much faster than d-c (80 per cent between 4 and 11 msec) and released somewhat more slowly (80 per cent between 4 and 18 msec).

There are a number of methods of slowing down the action of a relay. One group involves the use of some mechanical device connected to the armature. This may be an escapement, a pendulum or inertia device with or without a ratchet, or an oil or air dashpot. Operate or release times or both up to a minute or so can be obtained by such devices, but their weakness lies in the fact that most of them require so much mechanical work to complete a long operating cycle that the relay requires an excessive power input. If the delay mechanisms are made sufficiently light and frictionless to operate with small power inputs, they become too delicate and expensive for most applications. For most purposes where their somewhat large power requirements can be tolerated, motor-operated time switches have superseded these relay devices.

Probably the commonest and certainly the simplest way of slowing down a relay, but one that can be used only on d-c coils, is the use of a lag coil or slug. This is usually a large copper slug at one end of the winding, or a tubular sleeve between winding and core. The lag coil acts as a short-circuited secondary for the relay coil, and the counter magnetomotive force due to the current induced in it by the changing coil current delays the flux buildup or decay in the air gap and hence the closing or opening of the armature. A short slug near the armature end of the core has relatively more effect on the operate time and one at the heel end has more on the release time. A core sleeve affects both, and is more effective than a slug. Operate times up to 100 msec and release times up to 500 msec can be obtained in practice. These delays are rather sensitive to variations in the applied voltage; curves of operate and release time vs. voltage are given in Fig. 13·5.

Another type of relay that has not been greatly developed but which seems to have excellent possibilities is the thermal type. This is not an electromagnetic device but operates like a thermostat. It usually consists of a heater to which the control voltage is applied and some sort of thermally responsive mechanism that operates the contacts. It usually has snap-action contacts since the movement of the mechanism (normally a bimetal strip) is fairly slow, and it is often hermetically sealed. Delay

times of several minutes are possible. It is sensitive to variations in control voltage, but ambient temperature compensation is not particularly difficult. It is not very power-sensitive, but will operate on any type of current, even radio-frequency. An Edison thermal time-delay relay is shown in Fig. 13·6.

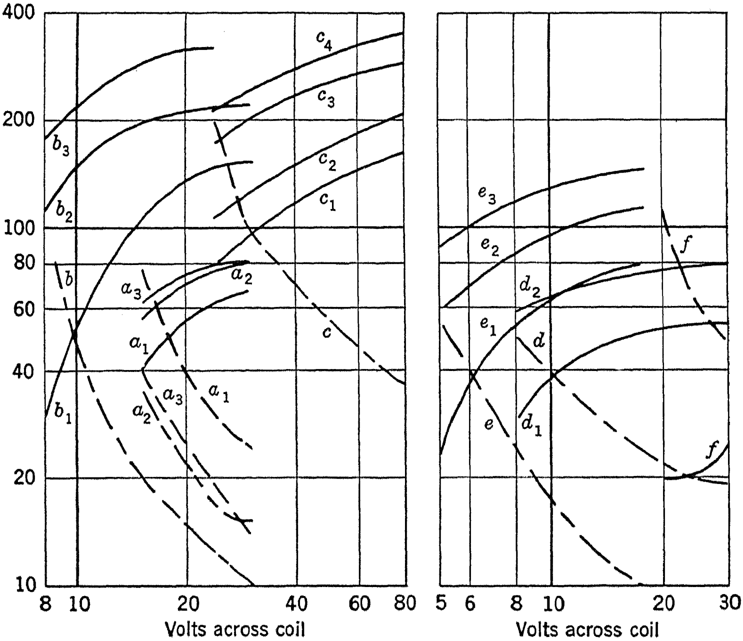


FIG. 13·5.—Operate and release times of lag relay. (*a*) Allied BOLX-4; short type, slug on heel of core, two curves for each of three samples. (*b*) Clare B-18466; long type, slug on heel of core, release curve b_3 is for minimum residual gap setting; operate time is unaffected by residual setting; release time is greatly affected. (*c*) Clare A-17978; long type, armature-end slug; release times would not repeat consistently for coil voltages above 80 volts. (*d*) Clare A-18466; long type, slug on heel of core; curve d_2 is for minimum residual gap setting. (*e*) Clare A-13960; short type, armature-end slug; curve e_3 is for minimum residual gap setting. (*f*) Guardian G-34464 type B-9; four heavy copper washers on armature end of core. (All operate-time curves solid; all release-time curves dashed.)

This same mechanism is frequently used to operate the coil of a power relay, with the thermal and electromagnetic units mounted on a single base. These relays usually have an auxiliary set of SPDT contacts to provide electrical lock-in of the power relay and to disconnect the heater as soon as it has functioned. This device considerably prolongs relay life and permits immediate recycling provided the power relay remains closed long enough for the heater to cool down.

A very simple thermal method of delaying the operation of a relay is to connect a self-heating thermistor (see Sec. 3·12) in series with the winding. Delays up to many minutes are obtainable, but the actual delay is very

sensitive to variations in ambient temperature, applied voltage, and relay operate current.

There are a number of methods of slowing down d-c relays by means of external delay circuits. If a large condenser or inductor is shunted across the relay coil, it will continue to supply energy from its own electrostatic or magnetic field to the relay winding for a time after the interruption of the control current. If the current source has a low internal impedance the operate time will not be much affected; if it does not have a low internal impedance the operate time will be prolonged. This method works best with high-impedance relay coils, since long delays with low-impedance coils require prohibitively large values of inductance or capacitance. The scheme is considerably more effective if the relay is connected in the plate circuit of a gas or vacuum tube and the delay circuit is connected to the grid; the very high impedance of the grid circuit plus the power amplification of the tube permit delay times of the order of minutes without requiring prohibitive values of reactance. Care must be taken in all LC-circuits to have enough resistance present

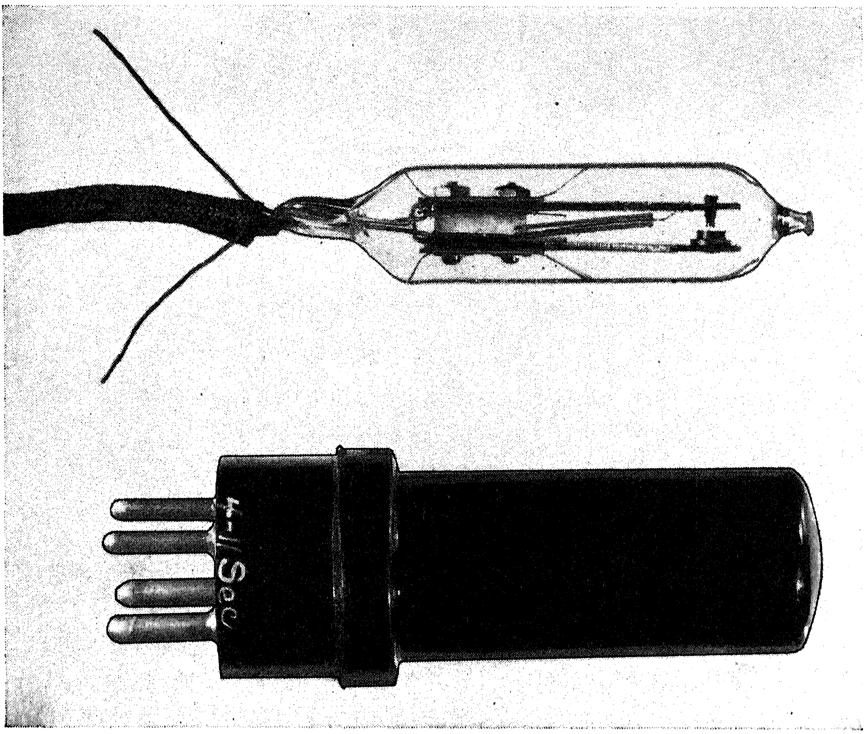


FIG. 13·6.—Thomas A. Edison, Inc., thermal time-delay relay.

to prevent oscillations, though it is possible to take advantage of the shape of the transient curve to improve the operation to some extent.

The added complexity, size, and weight involved in the use of the above systems renders them undesirable for many applications, particularly in combat equipment. Probably the best fixed-time-delay relay available for such purposes is the hermetically sealed thermal device, such as those made by Thomas A. Edison, Inc. and by the Amperite Company.

13·4 Other Aspects of Relay Design. *Shock and Vibration Resistance.* In some industrial and in all mobile applications, equipment is operated under conditions of vibration and shock that are particularly severe in aircraft and in military service. Airborne devices should function properly when vibrated sinusoidally in any direction at a maximum total excursion of $\frac{1}{16}$ in. at any frequency between 5 and 55 cps. For shipborne service the frequency range is lower and the amplitude somewhat higher. In addition, combat equipment must withstand shocks whose severity depends upon the type of service. Components installed in chasses that are properly vibration- and shock-isolated are not subjected to such severe conditions. Adequate vibration and shock resistance generally requires considerably more coil power than is necessary in normal service.

The results of an extensive series of vibration and shock tests on commercial relays are summarized in Sec. 13·7. In general it may be said, in spite of advertising claims to the contrary, that the majority of the types tested are unsatisfactory for many military applications, for which they were *not* designed. Their sensitivity to shock and vibration is primarily due to the lack of dynamic balance and the flexibility of the armature and moving contacts, to resonance in the contact arms, particularly when these are in the form of leaf springs, and to the general use of butt-type rather than wiping or knife-blade contacts. Adaptations of commercial designs, as by the addition of armature balance weights or the like, generally produce little improvement. Attempts to increase shock resistance by increasing coil power usually lead to operating temperatures too high for conventional coil constructions; this might be a partial solution if new insulating materials were used, such as Fiberglas and silicone insulating varnish. It would seem that a rotary type of relay with good dynamic balance, adequately strong mechanical construction, and knife-blade contacts might solve the problem, but at the expense of considerable increase in coil power and manufacturing cost.

Rotary Construction.—The possibilities of the rotary construction have impelled at least two manufacturers to produce such relays. The first in the field was Price Brothers Company, of Frederick, Md. They have brought out a number of types all based on the same magnetic structure and coil construction: several of these are shown in Figs. 13·7

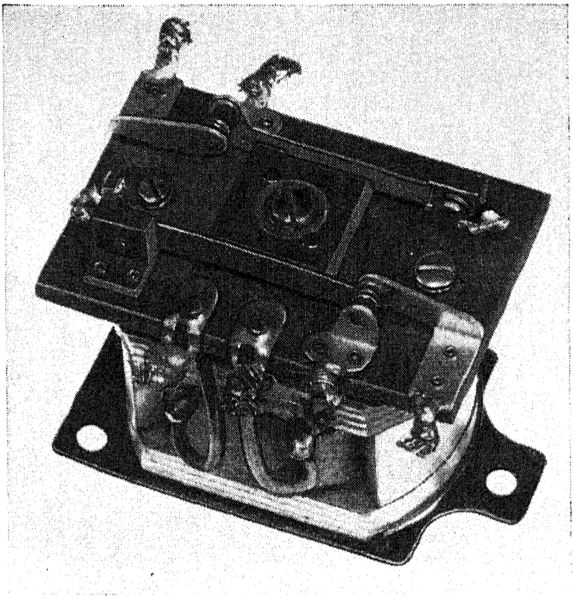


FIG. 13·7.—Price Brothers Company, Type 311 relay (No. 99, Table 13·5).

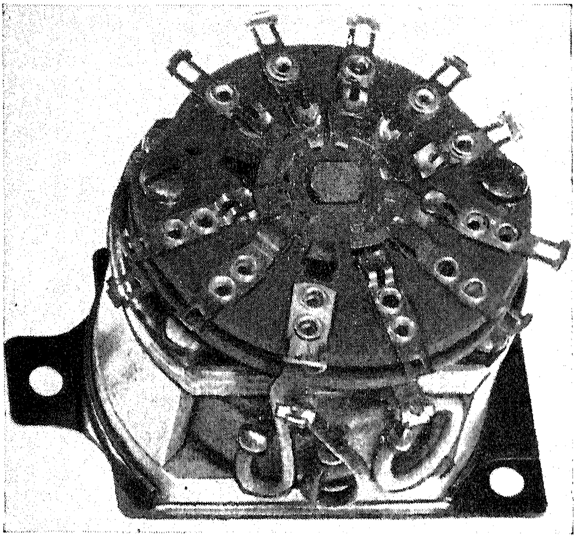


FIG. 13·8.—Price Brothers Company, Type 76-4 relay (No. 97, Table 13·5).

through 13·10. The contact mechanism of the Type 311 and the similar Type 310 (No. 98, Table 13·5) are more or less conventional, consisting of silver button contacts mounted on leaf springs that are actuated by bakelite cams mounted on the operating shafts. Type 76-4 and Type

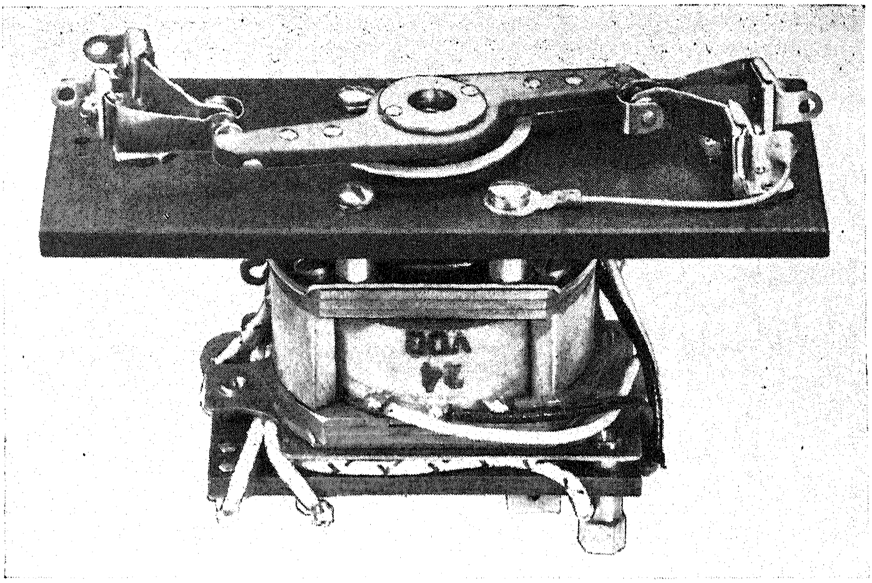


FIG. 13·9.—Price Brothers Company, antenna-transfer relay.

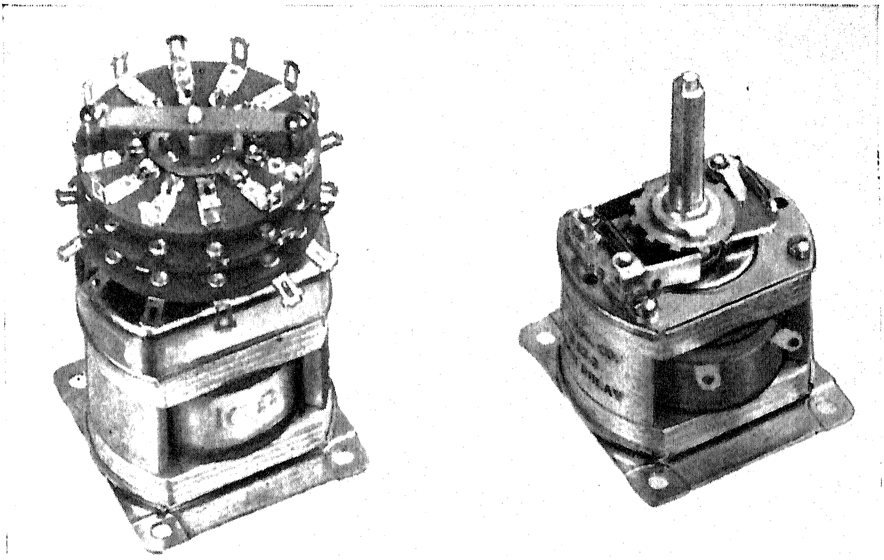


FIG. 13·10.—Price Brothers Company, Type 82-2 stepping switch and actuating mechanism.

82-2 utilize standard wafer-switch assemblies, which provide a simple and inexpensive means of building up switching assemblies of almost any degree of complexity from standard parts, since a wide variety of switch wafers is available on the market. Wafer switches provide an assembly

that is practically immune from contact bounce and is highly insensitive to shock and vibration. Such relays are somewhat sluggish, however,

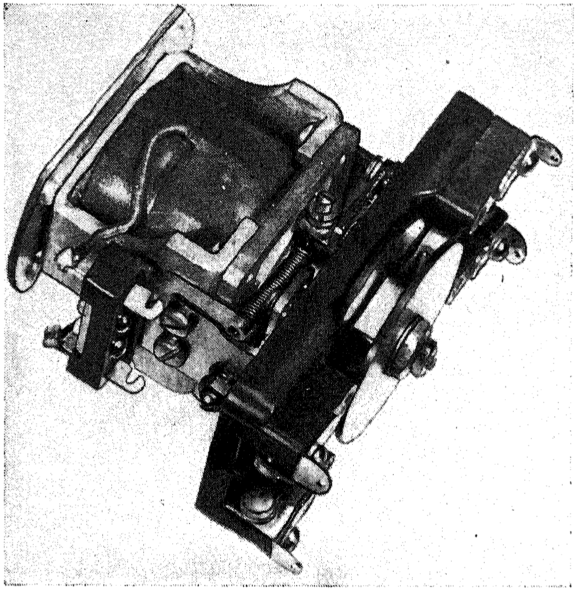


FIG. 13·11.—Allied Control Company Type RV-2 rotary high-voltage relay (No. 92, Table 13·5).

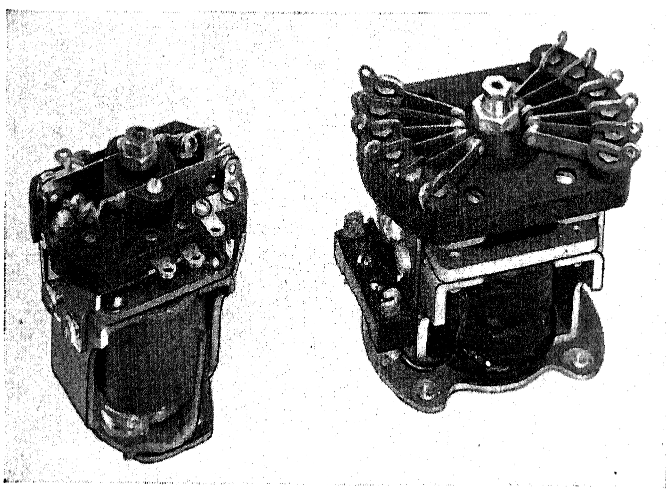


FIG. 13·12.—Allied Control Company experimental DPDT and 4PDT rotary relays.

and require an excessive amount of operating power for many purposes. The magnetic structure used in all these Price relays is the same; it is illustrated in Fig. 13·22*f*.

The Radiation Laboratory sponsored the development by the Allied Control Company of a series of rotary relays, some of which are shown in Figs. 13·11 and 13·12. The RV-2 was developed to switch circuits operating at several thousand volts in airborne equipment, and was fairly successful in that service. This success led to the development of low-voltage multipole relays for a Navy project where the relays had to pass the standard Navy shock, vibration, and salt-water immersion tests.

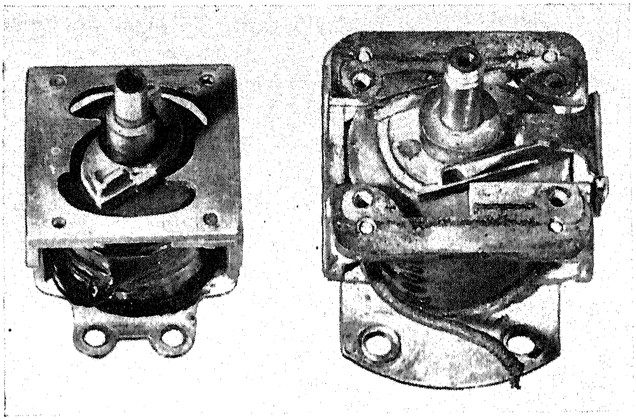


FIG. 13·13.—Magnetic structures of Allied Control Company rotary relays.

These relays were given the type numbers RMH-1, RMH-2, and RLH-3. The RMH is a 1000-ohm d-c relay with one NO DB and one 1 NC DB contact; it operates on 20 ma. The RMH-2 is identical except that it has a 5000-ohm coil intended for operation at 115 volts d-c and has DPDT contacts. The RLH-3 is a somewhat larger unit with 4PDT contacts and has a 3800-ohm 115-volt d-c coil. All three are mounted in hermetically sealed metal cans as shown in Figs. 13·14*a* and *b*. The magnetic structures are shown in Fig. 13·13.

All three of these units will pass the Navy salt-water immersion test; in fact the RMH-1 and RMH-2 were not injured when their cans were crushed by accidentally allowing the salt-water bath to freeze. The can of the RLH-3 opened a seam and filled with water, but in spite of this the relay operated after it was dried off. (The freezing test is *not* required in the specifications.)

The shock resistance of all three units was high, varying from 20- to 120-g acceleration required to cause momentary contact opening, depending upon the direction of the shock and the amount of excitation. An early experimental model of the RMH-2 was damaged by transverse shock, the can pulling loose from the base plate at the soldered joint. A redesigned and heavier base plate remedied that weakness.

All units satisfactorily withstood the Navy vibration test, except that after prolonged vibration at a critical frequency some of the frame screws loosened in spite of their lockwashers, and two of the cams rotated on the shafts. Both of these defects can easily be remedied in production.

The Allied relays, with the exception of the RV-2, were received too late to be included in the tests reported in Sec. 13·7 and were only tested for resistance to salt-water immersion, shock, and vibration. Their shock and vibration resistance is comparable to that of the Price Brothers Inc. rotary types and they require far less operating power. At the present time, they are certainly among the most satisfactory types available for the application for which they were designed.

Insulation.—Coil insulation will not be discussed here except to point out that in some applications severe surge voltages may appear across the relay coils. Extra insulation and wider spacing of the end turns may be required, or in some cases a protective glow tube, spark gap, or Thyrite resistor may be shunted across the coil. In some plate-current relays the coil will be at high voltage with respect to ground. This calls for extra insulation between coil and core, and in some cases for a modified construction of the relay.

The contact insulation in most relays is either laminated or molded phenolic plastic, though many manufacturers also supply ceramic-insulated types. Punched laminated sheet phenolics are particularly susceptible to water absorption and deterioration of the insulation. Molded plastics are somewhat better in this respect, and properly treated dense ceramics are much better. Ceramics, Mycalex, or low-loss plastics must be used when r-f currents are to be handled. Radio frequency usually calls for special contact construction to minimize the electrostatic capacitance between open contact pairs.

Tropicalization.—The entire structure of a relay—coil, contact assembly, and mechanical parts—must be specially treated in cases where it is to be used in the humid tropics or in other unfavorable climates. Insulating materials must be protected with fungicides by impregnation or lacquering, and metal parts must be proofed against corrosion. Much work has been done on this during the war, and numerous specifications for the various treatments have been issued, but the problem has not yet been completely solved.

Probably the best method, where it can be used, is the complete hermetic sealing of the whole relay in a suitable enclosure, as in the relays of Fig. 13·14*a*, *b*, *c*, and *d*. If the sealing is completely airtight, it also has the advantage of providing immunity to the effects of low atmospheric pressure at high altitudes. Incomplete protection is worse than none at all, however, since it discourages maintenance and may encourage condensation, fungus, and insects. If the sealed relay is

provided with a plug-in base, it greatly facilitates maintenance and testing of the equipment. The principal disadvantages of hermetic sealing are that it slightly increases size, weight, and cost and considerably increases the difficulty of adequately cooling the coil.

Servicing and Replacement.—Relay contacts are usually the greatest source of relay failures. For this reason, relays should always be installed if possible so that the contacts are accessible for inspection and servicing.

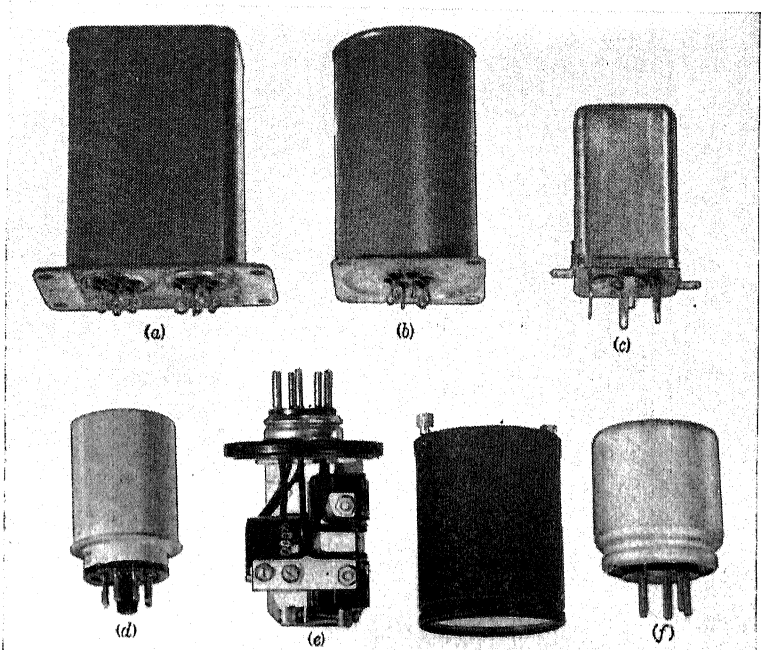


FIG. 13·14.—Relay enclosures. (a) Allied RLH-3; (b) Allied RMH-1; (c) Sigma 4RHP-50; (d) Clare SK-5001; (e) Sigma MX with removable dust cover; (f) GE CR 2791C103C25.

If this is not possible, as with sealed relays, great care should be taken to keep arcing at the contacts to a minimum.

This can often be accomplished by the use of arc-suppressing circuits across the contacts. These usually take the form of a resistor and a condenser in series. No adequate method is available to calculate the optimum values; it is usually best to start with about $\frac{1}{2}$ μfd in series with 10 ohms for 24 volts d-c or less on the contacts; for 24 to 110 volts about 1 μfd and 200 ohms will usually serve. Selection of the proper values is largely a matter of cut-and-try, the effectiveness of arc suppression being estimated by visual observation of the arc.

Replaceable contacts are usually provided on large relays and contactors, but this is not practicable on small units. The spring leaves on most small relays, especially the telephone types, are fragile and easily

bent. In many cases, especially in combat equipment, it is better to replace the whole relay than to try to service it in the field. Replacement is most easily done with the sealed plug-in units, and the easy replacement and the added protection of such units usually more than pay for the additional size and weight.

Relay Life.—If the coil does not run unduly hot, the life of a relay is usually the life of the contacts. The number of operations that a relay can satisfactorily perform depends principally upon the contact current and the rate of operation. Heavy contact currents cause contact heating and call for high contact pressures, which cause more rapid wear of both armature bearings and contacts. Contact temperatures may also become very high if the frequency of operation is too great to permit adequate cooling between operations.

Size and Weight.—The permissible size and weight of a relay depend upon the application. For most applications the average relay is not excessively large or heavy, but for airborne and portable equipment these factors become important. This often leads to working the materials of the relay near their endurance limits, with consequent shortening of the relay life. The weights of the relays tested at the Radiation Laboratory are given in Sec. 13·7.

13·5. Special Types of Relays.—Although neither space nor the available data permit anything like a complete listing of the low-powered relays available on the American market, it may be worth while to discuss briefly a few of the more specialized types that are regularly manufactured.

Relays with special forms of contacts have been referred to in Sec. 13·1. Most of the relay manufacturers supply relays with snap-action contacts; examples are the Automatic D55523G11 (No. 13, Fig. 13·15), the Sigma MX (Fig. 13·14*e*) and the Clare AMS and CMS series. Many makes of mercury contact relays are available; some operate by tilting the mercury container, such as the Automatic AMC, Clare M, and Dunco 22 and 91 series, while others use a stationary container and an internal magnetic plunger and a surrounding coil. The Dunco Type 22 is rather novel; its mercury contactors are mounted on a swinging topheavy arm that comes to rest against stops on either side of center, and a momentary current to the centered stationary coil swings the arm over the top to come to rest on the other side. Another interesting type is the Mercoid Type B transformer relay; this has a fixed primary and core and a short-circuited secondary that is free to move on an arm that is repelled from the primary in a way analogous to the old movable-secondary constant-current transformers used in series arc-lighting circuits.

Nonwelding contacts (tungsten, elkonite, carbon or metal-carbon

mixtures, etc.) are often used in relays for handling heavy inrush currents such as occur with tungsten-filament lamps and some types of motors. Such relays usually employ large-area flat contacts and very heavy contact pressures; examples are the Cutler-Hammer 6041H54A (No. 71, Table 13·3, Fig. 13·27*d*) and the Dunco 61 and 62 series. The Duncos, using special contact materials, handle inrush currents of as much as 1000 amp at 24 volts d-c with only 10 watts in the coil.

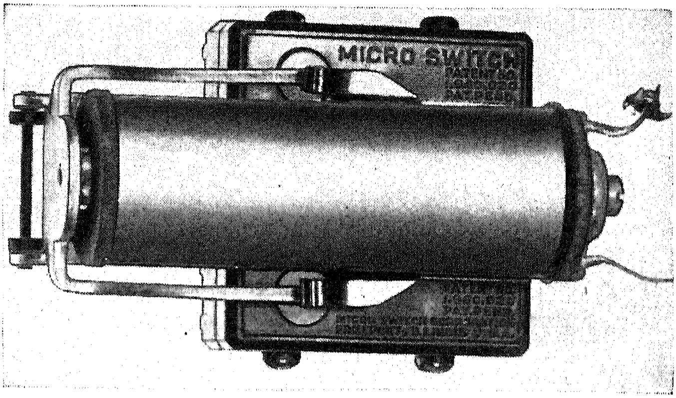


FIG. 13·15.—Automatic Electric Company D55523G11 relay.

Some manufacturers offer potential or current relays that operate either across or in series with the load. These are normally used as protective devices to shut down equipment in case of power supply failure; for example, a potential relay might be connected across a bias supply to disconnect plate power from a power amplifier in case of bias voltage failure, or a current relay might be connected in the cathode return of a modulated stage to remove plate voltage from a class-B modulator and protect the modulation transformer in case of loss of excitation to the modulated stage. Such relays are closely allied in function to underload and overload relays, that usually differ from the above only in having rather more definite operate and release points. An underload relay is often used with motor-generator battery charging sets to disconnect the battery and prevent discharging it back through the generator if the motor power fails. The ordinary cutout on an automobile generator is a similiar device with the addition of a potential winding that leaves the battery disconnected until the generator reaches charging voltage. Overload relays are used to disconnect power sources if load current (or sometimes voltage) becomes excessive. Some models such as the Advance 700, the Leach 1042-P (Fig. 13·16), and the Guardian X-100 must be reset manually; others such as the Advance 650 and the Leach 2417BF (Nos. 95 and 96, Table 13·5, Fig. 13·17) have auxiliary

coils to permit electrical resetting from a remote point. Dunco Types 55 and 56 are furnished in both forms. Overload and underload relays may have their operating points set at the factory, or they may be adjustable either by varying the air gap or the armature return spring, or by a rheostat in shunt with the coil.

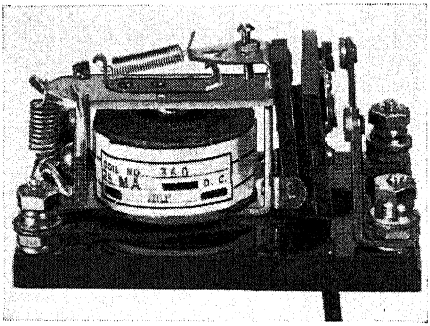


FIG. 13·16.—Leach Relay Company Type 1042-P manual-reset overload relay.

In some applications a relay is required which is sensitive to the direction of current flow. The automobile cutout is an example of this function; if the motor stops the potential winding will try to hold the contacts closed, but the current flowing from the battery to the generator in the discharge direction through the relay current winding will produce a counter magnetomotive force which will cancel that of the potential winding and will allow the armature to open. So-called polarized relays, however, almost always use permanent magnets to furnish the sense of direction, as in the Automatic PLD, the Dunco 19 and 59 series, and the Barber-Colman AYLZ-2022-1 (No. 94, Table 13·5). Polarized relays

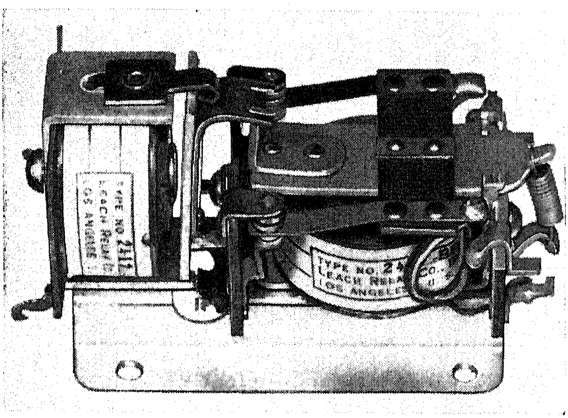


FIG. 13·17.—Leach 2417BF electrically reset latching relay.

are often highly sensitive and may be made for very fast and precise operation, especially for high-speed and multiplex telegraph operation.

Multiplex telegraphy also employs many high-precision nonpolarized relays such as the Automatic TQA. These are usually characterized by fairly high sensitivity, high speed, and accurately adjustable air-gap and contact spacings. They often employ either multiple windings on

the same core or mechanically-opposed magnetic circuits as in the Allied CS (No. 93 of Table 13·5, Fig. 13·18); many polarized relays such as the Barber-Colman unit above also use opposed coils for differential operation. This use of the word should not be confused with that of "close-differential" applied to such relays as the Dunco 49 or to moving-coil relays such as the Weston Model 705 and others (which are really meters with contacts added where the pointer would be ordinarily), and in which "differential" refers to the current range between the operate and release points. Thus "close differential" implies a release factor near 100 per cent.

Another type of relay used in communication circuits is the keying relay. Such relays are characterized by high operating speed and often

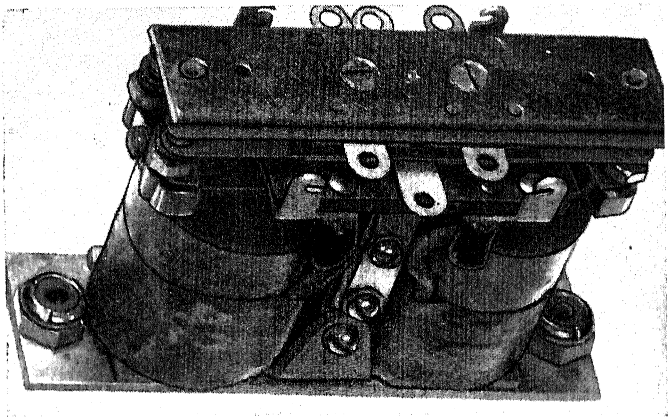


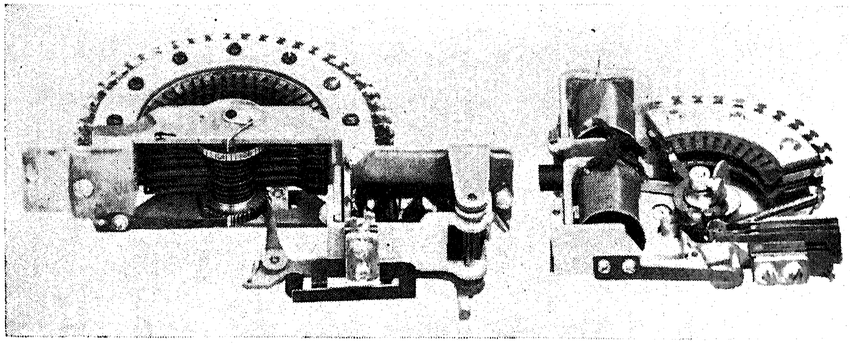
FIG. 13·18.—Allied CS differential relay.

by relatively great complexity of contact arrangement and function. A simpler type is the Allied AK. Many keying relays are normal types with increased contact insulation and spacing and decreased contact electrostatic capacitance, at least for the contacts used in the antenna circuit.

Ordinary relays are seldom built with more than six or eight poles, but there are special types that handle large numbers of circuits, such as the Automatic WGA and "Sunflower" types and the AEMCo Series HJ. These open or close a number of circuits simultaneously; there are also relays, usually called "line switches" or "stepping switches" that are electrically operated multiposition switches. These make contact successively between one contact arm and a number of individual contacts. There may be a number of such electrically independent decks. Examples of such stepping switches are the Automatic 204E and the Western Electric D87856F10 (Fig. 13·19) the Price 82-2 (Fig. 13·10), the Automatic "Minor" switch, the Guardian R, and a multitude of

different models made by Western Electric Company for automatic telephone exchanges.

Time-delay relays have been discussed previously; besides the lag relays such as those of Table 13·4, the Advance 300 and the Dunco PTAH1, PBAG1, PTBK1, and PTBL1 are examples of the thermal



(a) (b)
FIG. 13·19.—Stepping switches. (a) Western Electric D87856-F10; (b) Automatic Electric 204E.

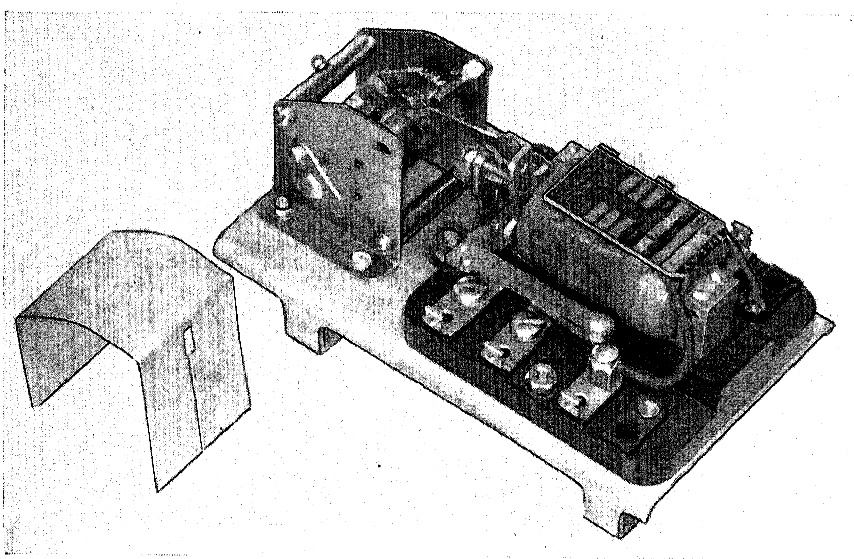


FIG. 13·20.—Escapement-type lag relay, Wheelock RX-9038-2.

type, the Dunco PW of the inertia type, the Agastat of the dashpot type, the Western Electric Company ESO-687119 (made by Signal Engineering and Manufacturing Company, Fig. 13·20) of the escapement type.

There are a number of purely thermal switches that could be used either as crude time-delay relays or as controlling elements for power

relays. The most common type is the combined toggle switch and circuit breaker so much used in domestic light and power distribution switchboards; it is actually a manually reset overload relay. Others such as the Edison and Amperite units referred to in Sec. 13·3 and the cheaper Klixon and similar units are actual time-delay units, and can be used as delay elements for power relays. Alternatively, thermostats such as the Fenwal could be thermally connected to a suitable heater element and used for the same purpose.

There are several classes of devices involving two or more relay elements plus electrical and mechanical interconnections. Several such multiple-unit devices have already been discussed, such as the electrically reset-overload relays and their close relatives, the latching relays. The Leach 2417-BF of Fig. 13·17 and the Dunco 5 and 51 types are examples of the latter class. Another class includes various mechanically interlocked relays such as the Dunco 38 where the armatures are so arranged that both cannot close at the same time, and the Allied BJU (Fig. 13·21) where the interlock bar actuates an over-center spring which ensures that either Relay *A* is closed and *B* open, or vice versa. Incidentally, most such relays that are intended for momentary contact operation will overheat if the coils are left excited for very long. Where this cannot be avoided, continuous-rating coils should be specified. This is true also of single-unit relays for impulse operation, such as the Dunco swinging-armature mercury relays and the cam-operated impulse relays such as the Advance 904A (Fig. 13·2) and the Dunco 11 and 85.

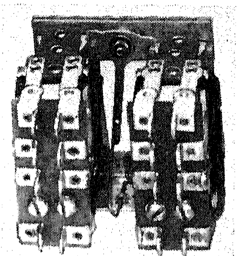


FIG. 13·21.—Allied Control Company Type BJU twin interlocked relay.

The preceding paragraphs by no means cover the field of special types of relays, but do give a suggestion of the stock types of special relays that are available. Most of the relay manufacturers are in a position to build variations and elaborations of stock types to order, especially if standard parts and subassemblies can be used. It is also possible in many cases to use several stock relays to perform special and often highly complicated switching operations by suitable electrical connections with or without mechanical modification or interconnection.[1]

13·6. Devices Related to Relays.—This section will be devoted to a brief description of several classes of components that are related to relays either in form or in function and that did not fall logically under any of the other chapter headings of this volume.

Solenoids and Actuators.—One useful class of devices that may be considered as relays minus their contact assemblies includes solenoids

[1] Packard, *op. cit.*, particularly Chap. IV.

and electromagnetic actuators, either rotary or linear. Several such units are shown in Fig. 13·22.

Solenoids are manufactured by a number of firms for both a-c and d-c operation and in a wide variety of sizes. An extensive line of industrial solenoids such as that of the General Electric Company includes several hundred different models for 25, 50, and 60 cps and for d-c operation at various voltages. These models are made up on ten different core and frame sizes, with useful pulls (or pushes, in most types) of from less

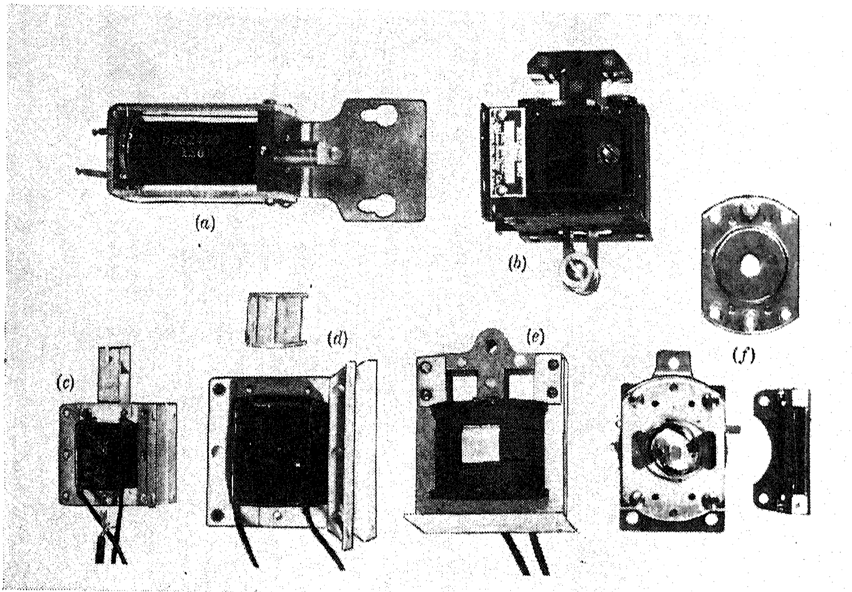


FIG. 13·22.—Solenoids and rotary actuator. (a) Automatic Electric D282479-130; (b) Allen-Bradley Bulletin 860 Series 2PPW; (c) D. W. Davis 1110A CD23; (d) D. W. Davis 2110A D-2 with armature removed showing shading coil; (e) National Acme 16KKK-100A; (f) Price Type 76 rotary actuator with housing and auxiliary contacts removed, showing shape of armature and pole piece.

than 1 lb to about 100 lb and with strokes of from $\frac{3}{4}$ to 3 in. Various accessories can be furnished, such as fittings to permit the unit to push as well as to pull (a push fitting is shown on the Allen-Bradley solenoid of Fig. 13·22*b*) and holding contacts to permit the use of a series resistor or holding winding in order to reduce the power consumption and heating of the main winding after the solenoid has closed. Alternating-current solenoids, except in the smallest and cheapest types used in single-stroke bells and the like, always use laminated magnetic structures with shading rings such as that shown in the end-on view of the armature of Fig. 13·22*d*. Many d-c solenoids use the same structures, but others, such as the Automatic Electric unit of Fig. 13·22*a*, use solid magnetic structures and

solid armatures. The metal coil heads, however, are usually slotted to reduce eddy currents and thereby to speed up the action of the unit.

Another device that is used to obtain translational motion and force beyond the practical range of a solenoid is the General Electric Thrustor. This is a self-contained combination of hydraulic cylinder, spring, and motor-operated pump, which looks somewhat like a rather ungainly hydraulic aircraft shock-absorber. It is useful for forces up to several hundred pounds and strokes up to a foot or more.

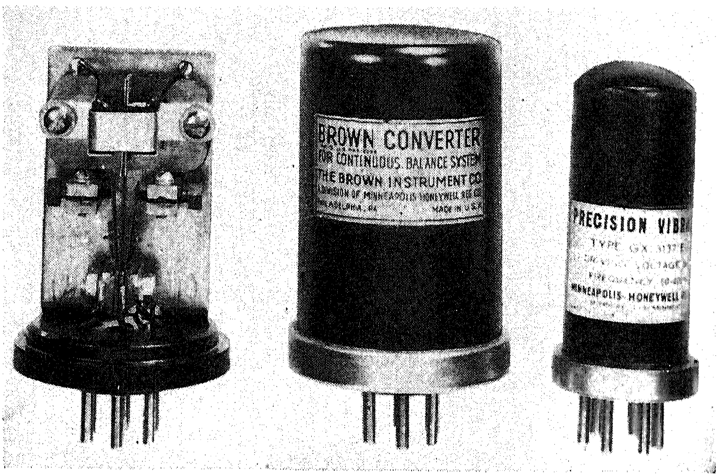
Most of the relay manufacturers will sell any of their models with the contact assemblies omitted, and on special order some of them will supply certain types of fittings to adapt the units to furnish forces of a few ounces at strokes of a fraction of an inch. Standard relay mechanisms are useful for operating latches or triggers, shutters, etc., in either experimental or production equipment. In some cases they may be used to furnish torques if the angular range of motion is small.

For applications in which the required torque or angular motion is beyond the range of a conventional relay mechanism a rotary actuator is useful. One such rotary actuator is the Price Brothers Company Type 76, shown in Fig. 13·22*f*. This particular model is intended for operation on 24 volts d-c. It has a throw of 60° and a torque of about 10 in.-oz. It is furnished with a holding coil and auxiliary contacts (shown disassembled in the photograph) to disconnect the main actuating coil at the end of the stroke, thereby permitting continuous excitation without overheating. A similar but more compact unit is the Ledex rotary actuator, manufactured by the Henry M. Leland Company of Cleveland. It has a stroke of 45° and a torque of 4 in-lb.

Instrument Vibrators.—A device which is closely related in structure to the power-supply vibrators of Chap. 12 but which is related to the relays since it is used as an electrically actuated switch is the instrument vibrator or Brown Converter, manufactured by the Brown Instrument Company of Philadelphia. This vibrator (shown in Fig. 13·23) is made in two forms. The larger, Fig. 13·23*a* and *b*, is intended for operation at 50 to 60 cps but can be used at somewhat lower or higher frequencies; the resonant frequency of the reed is 90 cps. The smaller model has been produced only in small quantities. It is intended for operation at 400 cps but has been used experimentally at considerably higher frequencies.

The Brown vibrator is not contact-driven, as is the case with a power-supply vibrator, but must be driven by a source of alternating current of the desired frequency. The standard coil is intended for 6.3-volt operation, but will work well at 9 volts without overheating. The stationary contacts are set at the factory so that all three contacts are connected for about $7\frac{1}{2}$ per cent of the operating cycle at standard

amplitude. The contact noise generated is of the order of 1 μv or less, being too low to measure. The usable power level is limited at the low end by electrostatic pickup from the coil and coil leads; the capacitance from coil and leads to the reed is about 5 $\mu\mu$f, which gives a pickup voltage on the reed of 1 μv at 60 cps if the reed works into a 100,000-ohm load. This pickup can be greatly reduced by opening the can and bringing the coil leads out of the top, away from the reed and contacts. The limitation at the high end of the power range is the burning of the contacts. A series of life tests was made on 16 vibrators at the Radiation



(a) (b) (c)
FIG. 13·23.—Brown Instrument Company vibrators. (a) 60-cps unit with cover removed; (b) standard 60-cps unit; (c) experimental 400-cps unit.

Laboratory and indicated that the contact life is indefinitely long at a current of 0.6 ma; at higher currents it decreases, being over 1000 hrs at 1.7 ma and less than 20 hrs at 4.5 ma. The contact current was supplied from a d-c source through a 10,000-ohm resistor. The end of the life of the unit was taken to be the point at which an appreciable change in performance was observed.

The standard Brown vibrator is mounted in a hermetically sealed metal can and plugs into a standard six-pin tube socket. These converters have been used in large numbers in apparatus designed by the Radiation Laboratory, particularly in servo circuits, precision voltage regulators, and computers, and have given excellent service. Their use should be even more extensive in the future. A discussion of their application to various problems will be found in Vol. 21 of this series.

Mercury Relay.—Another device that is intermediate in character between a conventional relay and an instrument relay is the Bell Tele-

phone Laboratories D-168479 mercury relay, a cross section of which is shown in Fig. 13·24. This is a glass-enclosed SPDT contact assembly in an inert gas under pressure. The contact surfaces are mercury on the surfaces of amalgamated Kovar or some similar alloy. The mercury supply on the contacts is maintained by capillary action from a quantity of mercury in the lower part of the glass bulb. The fixed contact spacing is such that in normal operation with the tube mounted vertically a momentary bridge of mercury connecting all three contacts is formed during the motion of the movable contact. The duration of this short-circuited condition increases as the tube is tilted, becoming continuous beyond about 45° from the vertical. The smallness of the parts and the use of the mercury permits high-speed operation with negligible chatter and comparatively large voltage- and current-handling capacity. The maximum current is limited to 5 amp averaged over 100 sec, 10 amp over 10 sec, or 50 amp over 10 μsec. Instantaneous voltages across opening or closing contacts should not exceed 500 volts. For these conditions the life at 60 cps should exceed 1000 hr.

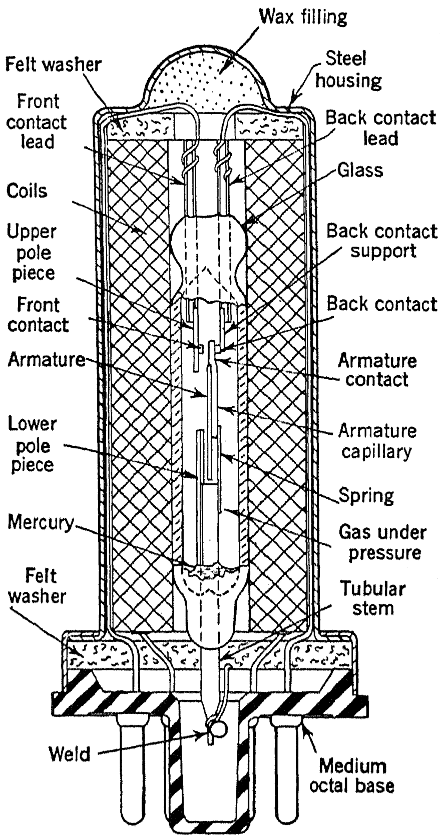


FIG. 13·24.—Bell Telephone Laboratories mercury relay. (*Courtesy of the Bell Telephone Laboratories.*)

The relay tube is enclosed in a steel shell and mounted on a standard octal tube base. The pin connections are as follows:

Pins 1, and 2, 700-ohm coil (5925 turns No. 40 enamel wire)
Pin 3, no connection
Pin 4, back contact
Pin 5, movable contact
Pin 6, front contact
Pins 7 and 8, 3300-ohm coil (16,950 turns No. 40 enamel wire)

Pins 1 and 8 may be strapped for a series-aiding connection of the coils.

The operating current with the coils series aiding is 6.6 ± 0.7 ma,

the release current 5.2 ± 0.7 ma. The continuity time for normal operation is 8 per cent maximum.

The mercury relay has been used principally in two types of service; as a "chopper," similarly to the applications of the Brown vibrator, and as a switching device to give 60-cps pulses with a duration that depends upon the magnitude of a control current. For the latter service the provision of two coils is convenient; an a-c current through one coil is provided to maintain the motion of the armature, and a variable d-c current through the other coil provides a variable d-c bias and varies the duration of the contact and thus of the output pulses. The mercury relay is a novel device and has interesting possibilities.

13·7. Relay Tests at the Radiation Laboratory. *Relay Data.*—Since relay failures and malfunctions had proved to be important sources of trouble in military electronic devices, and especially in airborne equipment, an extensive series of tests was carried out at the Radiation Laboratory on typical commercial relays such as were used in its equipment. Samples of over a hundred different models from a number of different manufacturers were tested, with particular emphasis on resistance to shock and vibration. This section is an abridged summary of the results of the tests; the original report[1] should be consulted for additional details.

Tables 13·1 through 13·6 and Fig. 13·31 present the data on 95 relays from 15 different manufacturers. The choice of types and manufacturers was largely arbitrary, being governed as much by the types that happened to be in stock as by any other consideration. An effort was made to choose a representative group of the types of relays that were of interest for military equipment, with some emphasis on the 24-volt aircraft class because of its importance and the severity of the conditions encountered in airborne service. In a number of cases pairs of relays were selected with the maximum and the minimum numbers of contacts in order to obtain both the least and the most favorable conditions for a given relay structure.

Because of the great amount of labor involved in the tests it was usually impossible to test more than two samples of each type. This gave a check on the consistency of the test results but the variations found between supposedly identical relays demonstrated conclusively that the tabulated values must be considered neither as accurate standards nor as statistical averages for the purpose of comparing types or makes. Relays are particularly subject to variation of characteristics due to minor changes in adjustment, and it is doubtful even that averages based upon large samples would have any great significance.

[1] H. Baur, "Relay Data Including Shock and Vibration Measurements," RL Report No. 747, Aug. 1, 1945.

Detailed comments follow on those columns of the tables for which the column headings are not self-explanatory.

In Column 2 the name of the manufacturer is given in abbreviated form. The full names and addresses of the manufacturers whose relays are included in the tables are as follows:

Advance Electric and Relay Co., 1260 W. 2nd St., Los Angeles, Calif.
Allied Control Co., Inc., 2 East End Ave., New York 21, N. Y.
Automatic Electric Co., 1033 W. Van Buren St., Chicago 7, Ill.
Barber-Colman Co., Rockford, Ill.
C. P. Clare and Co., 4719 Sunnyside Ave., Chicago 30, Ill.
Cutler-Hammer, Inc., 315 N. 12th St., Milwaukee 1, Wis.
General Electric Co., Schenectady 5, N. Y.
G-M Laboratories, Inc., 4313 N. Knox Ave., Chicago, Ill.
Guardian Electric Mfg. Co., 1400 Washington Blvd., Chicago 7, Ill.
Leach Relay Co., 5915 Avalon Blvd., Los Angeles, California.
Potter and Brumfield Mfg. Co., Inc., 617 N. Gibson St., Princeton, Ind.
Price Bros. Co., Frederick, Md.
R. B. M. Mfg. Co., Div. of Essex Wire Corp., Logansport, Ind.
Sigma Instruments, Inc., 70 Ceylon St., Boston 21, Mass.
Signal Eng. and Mfg. Co., 154 W. 14th St., New York, N. Y.

Column 4 gives the nominal coil voltages in volts. This is a rather meaningless quantity, as consideration of the other data will demonstrate, particularly in the case of relays intended for plate-circuit operation. It is principally of use as a basis from which to design coils for other relays of identical construction for operation on other voltages. It must be used with caution in attempting to compare the performance of relays of different types.

Column 5 gives the contact classification, noting in order, poles, throws, normal position, breaks. Thus SPST NO DB signifies as a single-pole single-throw normally open double-break relay. Normally closed is signified by NC. All contacts are single-break except when noted as DB. When relays have several sets of differently functioning contacts the several groups are separately listed; thus DPDT + 1 NO DB would mean a double-pole double-throw relay with an additional set of normally open double-break contacts. Naturally NO and NC are used only for single-throw contacts.

Column 6 gives the contact rating in amperes. This rating is not necessarily the same for all contact groups of the same relay, and depends greatly upon operating conditions as explained in Sec. 13·1. The values given in the table must not be used as a guide to the application of a

particular relay; they are included only to indicate what the relay is supposed to be capable of doing under normal conditions.

Column 8 gives the d-c coil resistances in ohms at 25°C, rounded off to the nearest 5 or 10 ohms except in the case of low-resistance coils. The resistances of supposedly identical coils were usually the same within 1 or 2 per cent.

Column 9 gives the temperature rise in degrees centigrade above a 65°C ambient temperature. Most of the relays were tested at 125 per cent of nominal coil voltage; the actual per cent voltage used (or the applied voltage, in the case of relays for which no nominal voltage was specified) is given in parentheses for the other relays. This choice of ambient temperature and overvoltage is admittedly a severe test, but is not unreasonable for military equipment in view of the high ambient temperatures encountered in crowded chassis and the poor voltage regulation of field power sources. Coil temperatures were determined by resistance measurements, and the tabular values are rounded off to the nearest five degrees.

Columns 10, 11, and 12 give respectively the coil input in watts at nominal voltage and 25°C, the minimum input at 25°C necessary to operate the relay, and the ratio of the minimum to nominal input expressed in per cent. Coil powers were not measured for the a-c relays.

The release factor in Column 13 is 100 times the maximum release current (or voltage) divided by the minimum operate current (or voltage). It is a measure of the "differential" of a relay, a zero differential corresponding to a release factor of 100 per cent. Minimum operate current (for d-c relays) is the minimum coil current that will operate the armature, opening all NC contacts and closing all NO contacts. In the case of a-c relays, minimum operate voltage is the minimum voltage that, when applied to the coil at 25°C, will perform the same function, the contacts being closed tightly enough to prevent momentary opening due to contact chatter. The point of minimum a-c operating voltage is not as sharply defined as that for d-c current.

Maximum release current is that value of (d-c) current that will just permit the previously energized armature to drop out, opening all NO and closing all NC contacts. Release (a-c) voltage is that voltage at which the closed NO contacts just begin to chatter open, as shown by a sudden large increase in the contact resistance.

The table gives the maximum and the minimum values of release factor obtained for any sample of each type. When only one value is given it may mean either that only one sample was tested, or that all samples gave the same value.

The last five columns of the tables give the operate and release times in milliseconds. Operate time is the total elapsed time from the applica-

tion of voltage to the relay coil until all NO contacts close and all contact bouncing ceases. Release time is the total elapsed time from the breaking of the coil circuit until all NC contacts close and bouncing ceases. In the case of multiple-pole relays all NO contact pairs were wired in series, and likewise all NC pairs.

Columns 14, 15, and 16 give respectively the maximum operate time observed for any sample at minimum coil voltage, the average time at nominal voltage, and the minimum time at maximum voltage. For the

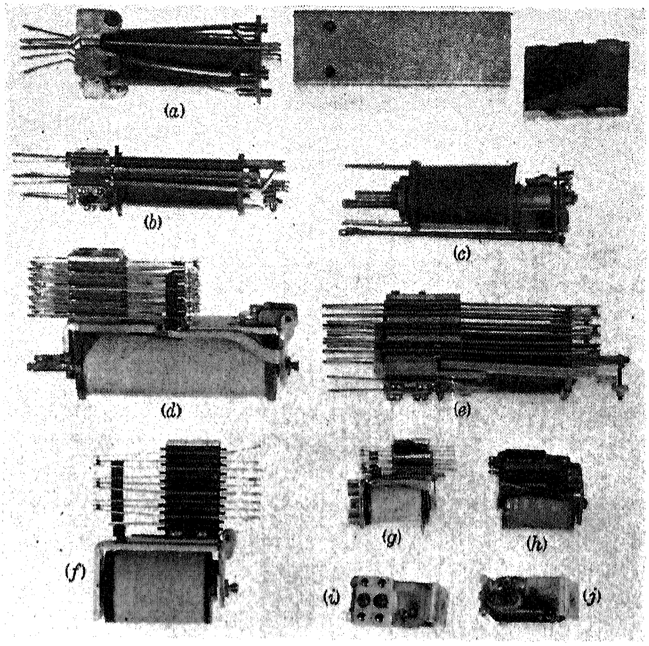


FIG. 13·25.—Typical telephone-type relays. (*a*) Western Electric B-1018 with cover and lid removed; (*b*) Western Electric R-323; (*c*) Western Electric 208-B; (*d*) Clare A-11906; (*e*) Western Electric 41/U692; (*f*) Clare A-11137; (*g*) Clare A-22023; (*h*) Automatic Electric H-77734-7; (*i*) Allied TSL-C low-capacitance type; (*j*) Allied TSL-C standard type.

release times, which are much more consistent and nearly independent of applied voltage, the maximum and minimum observed values are given in Columns 17 and 18. Because operate time in particular is greatly affected by relay adjustment the tabulated figures are not significant in themselves, but do give a rough idea of what performance may be expected. In the case of the a-c relays only maximum and minimum values are given for the operate times. In the case of the slug-type lag relays the operate- and release-time curves have already been given in Fig. 13·5.

Figures 13·25 through 13·29 show a number of typical small relays of

various types. Relays identical with those listed in Tables 13·1 through 13·6 were chosen as far as possible.

Vibration and Shock Tests.—Contact opening in the vibration and shock tests was detected by an electronic indicator whose response time

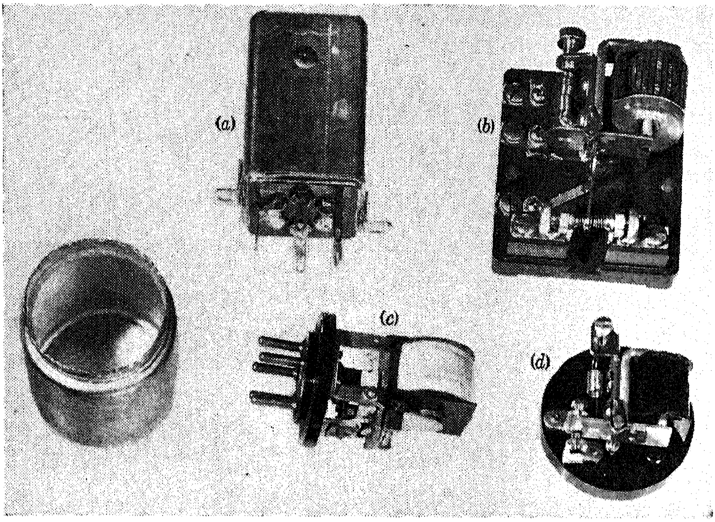
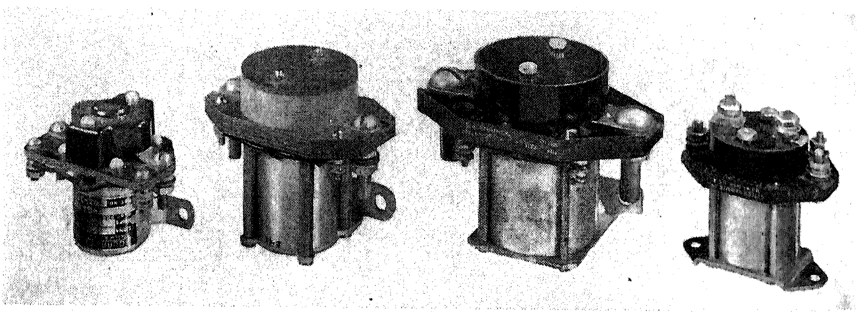


FIG. 13·26.—Typical sensitive relays. (*a*) Sigma 4RHPL; (*b*) Allied BD-330; (*c*) General Electric CR2791C104C23 with cover removed; (*d*) Allied G.



(*a*) (*b*) (*c*) (*d*)

FIG. 13·27.—Small d-c motor contactors. (*a*) Square-D class 9350 Type B5A; (*b*) Leach B6; (*c*) Cutler-Hammer 604H14A; (*d*) Cutler-Hammer 6041H54A.

was a few microseconds. The vibration tests were made on a Type VUDM Vibration Test Table made by the LAB Corporation of Summit, N. J., the amplitude being held constant at 0.03 in. (total excursion 0.06 in.) and the frequency gradually increased from 0 to 55 or 60 cps, or until the contacts opened. The peak acceleration in g's is given by $A_g = 0.0511Df^2$, where D is the total displacement in inches and f is the frequency in cps. The shock tests were made on an American War

Standard C29.3-1943 Shock Testing Machine, made by Radio Frequency Laboratories, Inc., Boonton, N. J. The relays were rigidly mounted on the shock table and successively greater drops were made until the contacts opened. For the particular spring used, the acceleration was given by $A_g = 203 \sqrt{S/W}$, where S is the drop in inches and W is the total weight dropped, in pounds. In these tests W can be taken as constant at 10 lbs within the accuracy of the tests, which is estimated at ± 10 per cent. It was found that variations of 15 to 20 per cent in

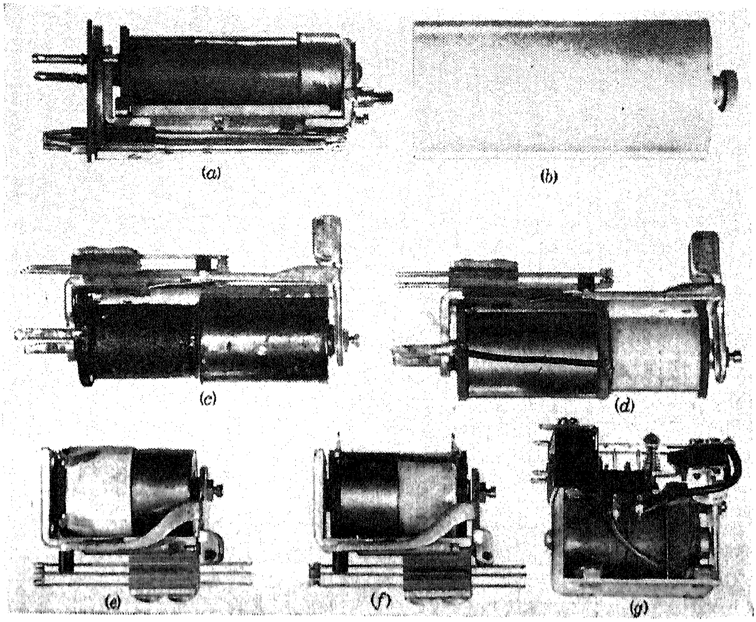


FIG. 13·28.—Slug-type lag relays. (a) Western Electric 178-BD with cover removed; (b) cover for 178-BD; (c) Clare A-18360; (d) Clare B-18466; (e) Clare A-13960; (f) Clare A-18466; (g) Allied BOLX-4.

drop height were obtained from successive tests of the same relay; this may have been due to variations in the seating of the armature after the previous shocks, or to high-frequency accelerations associated with the impact.[1] The lowest value of drop at which the relay opened was the one recorded.

The coil currents used in the shock and vibration tests were those corresponding to minimum expected operating voltage at maximum hot coil resistance. In the case of the 24-volt d-c relays these currents usually corresponded to coil voltages between 17.5 and 19 volts at 25°C; accordingly all these relays were tested at 18.5 volts. Many of the a-c relays chattered at the calculated coil currents; the current was therefore

[1] Dr. Irwin Vigness, N.R.L. Report No. 0-1414, 5 Dec. 1944.

TABLE 13·1.—GENERAL-PURPOSE D-C RELAYS

Relay no.	Make	Maker's no.	Nominal coil voltage, v	Contact arrangement	Contact current rating, amp	Weight, g	Coil resistance at 25°C, ohms	Temp. rise above 65° ambient, degrees C.	Operating power, watts: normal	Operating power, watts: min.	Operating power, watts: per cent	Release factor, per cent	Operate time, msec: max.	Operate time, msec: average	Operate time, msec: min.	Release time msec: max.	Release time msec: min.
1	Allied	BJ6D36	24	DPDT	5	90	250	60	2.30	1.10	50	36–54	24	12.5	8.5	8.5	3
2		BJC6D36	24	DPDT	5	100	275	55	2.10	1.05	50	59–69	37	14	8.5	9	3
3		BO6D35	24	DPDT	15	127	230	60	2.50	1.47	60	36–48	34	27	17	5	5
4		BO12D35	24	4PDT	15	158	235	55	2.45	1.37	60	74–78	35	22	15	10	10
5		BOY6D35	24	DPDT	10	141	635	35 (175)	0.91	0.40	40	22	36	24	12	13	5
6		BOY6D42	87	DPDT	10	140	10250	40 (185)	0.74	0.29	40	37–43	38	25	15	15	8
7		BN18D33	24	6PDT	10	297	175	60	3.30	2.76	80	37–58	50	42	28	6	6
8		PC-14	24	DPDT	5	108	2565	0	0.22	0.15	70	42	55	33	25	....	....
9		TKL-CC	24	DPDT	1	50	300	50	1.92	0.32–0.66	20–30	44–52	18	10	6	5	4
10		TKL-CC-CC	24	DPDT	1	54	295	50	1.95	1.40	70	48–56	30	19	12	5	4
11		TSL-C	24	SPDT	1	33	600	30	0.96	0.28	30	44–65	20	9	6	4	2
12		TSL-CC	24	DPDT	1	37	380	45	1.51	0.77	50	44	30	12	7	5	4
13	Automatic	Z11590	24	SPDT	1	39	3000	5	0.19	0.09	50	75	75	33	13	5	3
14		283384	24	4PDT	1	52	510	35	1.13	0.46	40	53–58	32	15	9	3	3
15		D55523G11	50	DPDT	10	339	11000	10 (260)	0.23	0.16	70	23–29	...	180	35	5	5
16	Clare	A11191	24	4PDT	3	53	180	70	3.20	1.39	40	51–63	20	13	8	6	3
17		A11906	50	8PDT	3	331	2500	45 (260)	1.00	0.69	70	59–73	...	80	30	6	6
18		A19657	24	SPDT	3	35	300	60	1.92	0.40	20	51	10	6	4.5	3	3
19		A21136	26	SPDT	3	38	300	55 (115)	2.25	0.35	20	44–48	15	6	4.5	4	4
20		B19657	24	See Note	3	42	300	45	1.92	0.85	40	55	15	9.5	7	4	4
21		SK5001	24	DPDT	3	70	300	65	1.92	0.56	30	53–75	26	9	6	5	3
22	GE	CR2791B100C2	14	SPDT DB	20	107	72	40 (107)	2.72	0.52	20	48	26	13	11	18	18
23		CR2791D100F3	24	DPDT DB	8	175	108	80	5.34	2.26	40	27–32	32	24	17	25	23
24	G.M. Lab.	12842	70	DPDT	2	157	10000	20 (215)	0.49	0.34	70	53	90	63	18	5	5
25		12848	3.5	SPST NO DB	15	161	17	15 (230)	0.72	0.50	70	82	...	48	12	....	....
26		12934	24	SPDT	4	170	133	50	4.33	1.33	30	23	35	22	17	5	5
27		12965-4	24	SPDT DB	15	144	283	30	2.04	0.63	30	21–27	35	27	19	7	7
28		12968-2	2.5	DPDT	15	160	16	55 (320)	0.39	0.23	60	27	40	24	12	6	6
29		12968-8	70	DPDT	15	160	5700	30 (185)	0.86	0.60	50	33	...	55	18	8	7
30		12986	50	4PDT	4	165	3600	25 (200)	0.70	0.60	90	38–46	...	.....	12	6	6
31		12992	70	3PDT	4	160	10500	20	0.47	0.43	90	31–40	...	.....	28	10	10
32		13116	24	SPDT	1	273	2400	5	0.24	0.06	30	50–54	120	60	46	7	7
33		13117	24	8PDT	1	340	240	25	2.40	0.51	20	66–71	70	49	37	7	7
34	Guardian	33177	26	3PDT	12	197	170	45 (115)	3.98	1.70	40	32–35	45	34	28	9	9
35		33615	24	DPDT	12.5	137	150	70	3.84	2.06	50	40–48	40	33	24	13	10
36	Leach	1029MBFW	110	4PDT	4	157	9950	20 (118)	1.22	1.03	80	33–42	65	47	20	25	20
37		1057RWBF	24	DPDT	6	156	165	55	3.50	1.02	30	21–23	26	17	12	10	10
38		1423RW	24	SPDT DB	6	215	168	55	3.42	1.62	50	59	40	29	22	42	42
39		1457MX	24	DPDT	6	230	160	75	3.60	0.72	20	22–28	22	16	13	5	2.5
40		1601MX	24	SPST NO DB	25	167	255	40	2.26	0.24–0.55	10–20	44–55	27	19	16	3	3

41	P & B	KLD-1	24	SPDT	3	96	300	40	1.92	1.11	60	73–78	9	6	5	....	....
42		KLD-10	24	4PDT	3	128	295	40	1.95	0.81	40	42–57	40	24	15	10	8
43		KRD-4	24	SPDT	3	52	515	35	1.12	0.31	30	57	17	9	7	16	11
44		SPD-1	24	SPDT	5	121	235	50	2.45	0.64	30	37	24	13	10	5	5
45	Price	18-B	45	DPST NO DB	5	138	175	15	0.82	0.35	40	37	20	18	14	....	....
46		501	10–14	DPDT	0.25	71	77	40	1.87	1.02	60	33	33	23	15	5	4
47		551	8–12	3PST NO	0.25	55	77	40 (150)	1.30	0.65	50	61	28	20	9	....	....
48	R. B. M.	GX23500	26	4PDT	1	66	250	55 (115)	2.70	0.47	20	29	18	10	7	5	5
49		23005	26	SPDT	1	41	290	60 (115)	2.33	0.46	20	49–54	19	7	5	5	4
50	Sigma	4AH	90	SPDT DB	1	111	11000	30	0.74	0.64	90	39–42	...	19	6	10	10
51		4RHP-50	2.5	SPDT	1	156	47	40 (360)	0.13	0.11	80	86	...	.....	25	0.5	0.5

NOTES:
Relay No. 15: Uses 2 BRL-2 Microswitches. See Fig. 13·15.
Relay No. 20: Contacts SPDT + 1 NO make before 1 NC break.
Relay No. 21: Hermetically sealed on octal base. See Fig. 13·14*d*.
Relay No. 50: Sealed dust cover on 5-pin plug-in base.
Relay No. 51: Hermetically sealed. See Fig. 13·14*c*.

TABLE 13·2.—SENSITIVE D-C RELAYS

61	GE	CR2791C103C25	10	SPDT	1	109	2300	30 (500)	0.044	0.027	60	68–77	...	25	2	4	2
62	Price	MD400	6	SPDT	0.25	25	465	20 (333)	0.078	0.035	40	47	38	16	10	8	5
63	Sigma	3A500	2.5	SPDT	1	130	488	45 (1200)	0.013	0.013	100	90	...	27	5	7	7
64		4F200	1.5	SPDT	1	66	290	40 (1330)	0.011	0.006	60	75–90	...	18	2	2	1
65		4M	7.5	SPDT	1	100	7600	35 (1730)	0.007	0.006	70	51–56	...	.....	18	22	8
66		4RHPL-1000	8	SPDT	1	156	1000	30 (440)	0.064	0.064	100	65–70	...	40	6	5	5
67	Signal	RB-4	6	SPDT	0.5	179	4800	25 (1660)	0.008	0.005	60	16	120	80	20	70	70

NOTES:
Relay No. 61, 63, 64: Dust cover and 5-pin plug-in base.
Relay No. 66: Hermetically sealed. See Fig. 13·14*c*.
Relay No. 67: Weight without cover.

TABLE 13·3.—SMALL D-C MOTOR CONTACTORS

71	C-H	6041H54A	24	SPDT DB	50	310	100	65	5.76	release 2.03	35	22–41	30	21	15	14	11
72	Leach	7220-4-24	24	SPST NO DB	200	408	8.5	45	69.0	....	..	...	30	21	16		

NOTES:
Relay No. 72: Has double winding; low-resistance winding cut out by series NC contacts on operation. Normal input 69 watts to low-resistance coil; holds on less than 1 watt.

TABLE 13·4.—SLUG-TYPE LAG RELAYS

Relay	Make	Maker's no.	Nominal coil voltage, v	Contact arrangement	Contact current rating, amp	Weight, g	Coil resistance at 25°C, ohms	Temp. rise above 65° ambient, degrees C.	Operating power, watts			Release factor, per cent
									normal	min.	per cent	
81	Allied	BOLX-4	24	DPDT	10	223	230	60	2.50	0.37	20	47–54
82	Clare	A13960	.....	SPDT	4	211	83	75 (20 v.)	......	0.25	..	59–67
83		A17978	24	SPST NO	3	347	2000	30 (365)	0.29	0.19	20	19–95
84		A18466	.....	SPDT	4	211	80	55 (20 v.)	......	0.20	..	25–38
85		B18466	.....	SPDT	4	328	250	40 (30 v.)	......	0.17	..	26–46
86	Guardian	G-34464	24	DPDT	15	198	190	50	2.96	0.17	20	41

Operate- and release-time curves given in Fig. 13·5.

TABLE 13·5.—MISCELLANEOUS SPECIAL RELAYS

Relay	Make	Maker's no.	Nominal coil voltage, v	Contact arrangement	Contact current rating, amp	Weight, g	Coil resistance at 25°C, ohms	Temp. rise above 65° ambient, degrees C.	Operating power, normal	Operating power, min.	Operating power, per cent	Release factor, per cent
91	Advance	904A	110 v. 60 ~	DPDT	10	242	23	100	......	....	..	100
92	Allied	RV-2	24 v. d.c.	1 NO+1NO DB	10	390	176	40	3.27	1.49	50	14–19
93		CS	24 v. d.c.	DPDT	5	199	8000	5	0.072	0.059	80	90
94	B-C	AYLZ-2022-1	24 v. d.c.	SPDT	0.5	162	930	25	0.62	0.0006	0.1	97
95	Leach	2417-BF	24 v. d.c.	DPDT	4	225	250	45	2.30	0.81	40	...
96	Price	2417-BF	115 v. 60 ~	DPDT	4	225	530	40	......	....	..	...
97		76-4	24 v. d.c.		1	279	7.5	25	77	14.6	..	...
98		310	12 v. d.c.	3PDT	40	398	9	10	16	0.54	..	...
99		311	40 v. d.c.	DPDT	5	325	1870	50 (250)	0 855	0 55	60	96

NOTES:
Relay No. 91: Ratchet-and-cam operated sequence relay; "on"—"off"—"on"—etc. Coils rated for momentary duty only. See Fig. 13·2.
Relay No. 92: Rotary relay for high-voltage operation; 8-kv insulation. See Fig. 13·11.
Relay No. 93: 3-position sensitive differential relay; 2 independent coils and magnetic circuits mechanically opposed. Center "off" position. See Fig. 13·18.
Relay No. 94: 3-position high-sensitivity differential polarized relay. 2 windings, center "off" position.
Relay No. 95, 96: Latching relay with electrical release. Coils normally operated only momentarily but rated for continuous excitation. See Fig. 13·17.
Relay No. 97: Rotary relay with wafer-switch contacts and double winding. Normal input to low-resistance winding 79 watts; to holding winding 2.2 watts. Will hold with 0.2 watts. See Fig. 13·8.
Relay No. 98: Rotary relay with double winding. Normal input 16 watts to low-resistance coil, 1.1 watt to holding coil. Will hold with 0.15 watt.
Relay No. 99: Rotary relay. See Fig. 13·7.

TABLE 13·6.—GENERAL-PURPOSE A-C RELAYS

Relay no.	Make	Maker's no.	Nominal coil voltage, v	Contact arrangement	Contact current rating, amps	Weight, g	Coil resistance at 25°C, ohms	Temp. rise above 65° ambient, degrees C.	Release factor, per cent	Operate time, msec		Release time, msec	
										max.	min.	max.	min.
101	Allied	BJ6A115	110	DPDT	5	92	645	70	93	11	4	8	5
102		BJC6A115	110	DPDT	5	101	640	65	87–94	4	3	10	5
103		BO6A115	110	DPDT	15	140	450	30	89–95	14	6	12	11
104		BO9A115	110	3PDT	15	161	300	50	95	12	5	7	7
105		BO12A115	110	4PDT	15	169	300	50	94–98	10	4	10	10
106		BN18A33	110	6PDT	10	298	175	35	95	11	5	13	5
107	Clare	B20392	115	4PDT	3	183	150	80 (120)	94	14	7	11	11
108		B21276	115	DPDT	4	167	215	40 (115)	92	7	5	7	5
109		400	120	DPDT	3	73	215	35 (120)	85–90	4	2	4	4
110	Guardian	A34990	110	3PDT	12.5	198	385	55	94	13	10	25	22
111	Leach	1127BFRW	110	DPDT	4	137	540	50	88–93	8	8	12	12
112		1157RWBF	110	DPDT	6	149	520	50	93–95	10	7	19	19
113		1157CRWBF	110	3PDT	6	150	510	55	82–95	10	6	18	15
114		1326DEW	110	1 NO DB + 1NC	25	191	360	65	88–91	13	10	25	23
115		1557MX	110	DPDT	6	226	525	55	92–94	20	15	27	27
116		1701MX	110	SP NO DB	25	226	520	50	87–94	11	6	..	..
117	P & B	KLA-1	115	SPDT	3	100	540	40	86–92	10	5	13	13
118		KLA-10	110	4PDT	3	112	540	35	88–94	12	7	17	17
119		KRA-4	115	DPDT	3	50	3130	25	86–90	10	7	20	20
120		SPA-1	110	SPDT DB	5	118	1235	35	87–90	11	7	9	7

NOTES:
Relay No. 109: For 400-cps operation. All other a-c relays in tables intended for 60-cps operation.

increased to the minimum value at which the contacts would remain closed.

The resistance of a relay to shock and vibration depends upon the direction of the resulting acceleration, and therefore the relays were tested in three directions. The notation used for these directions is explained in Fig. 13·30. Relays were divided into six classes depending

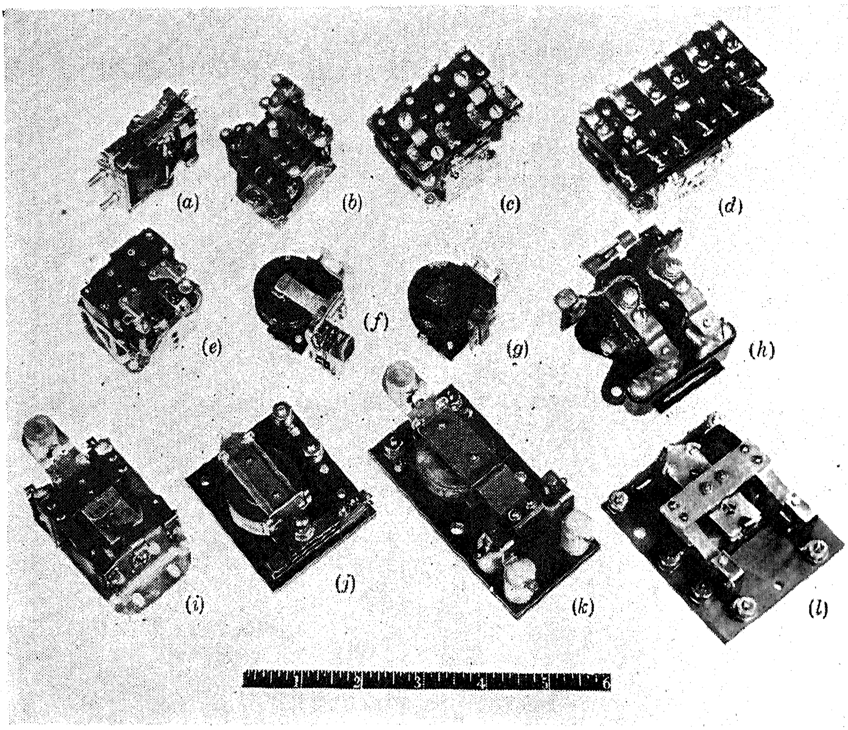


FIG. 13·29.—Typical small general-purpose relays: (*a*) Allied BJ6D36; (*b*) Allied BO6A36; (*c*) Allied BO12A115; (*d*) Allied BN18A115; (*e*) G-M Laboratories 12968-8; (*f*) Clare A23164 400-cps relay; (*g*) same with armature and contacts removed, showing laminated magnetic structure and shading coil; (*h*) Potter and Brumfield PRA-4; (*i*) Leach 1157RW-BF; (*j*) Leach 1020 (note MBB contacts); (*k*) Leach 1423-RW, Mycalex base, high-voltage insulation; (*l*) Leach 1507-MX, Mycalex base, for radio frequency.

upon the mechanical structure of the armature and moving contact assembly. For most of these classes the X-axis was taken parallel to the coil axis and the Z-axis parallel to the armature pivot axis. The actual choice between positive and negative direction along the three axes is not distinguished in the figure, but in the tests the least favorable direction was usually chosen.

Figure 13·31 presents the results of the tests in semiquantitative form. In the case of the vibration and shock tests, quantitative results were available and six grades were set up, with the following limits:

For the vibration test:

X = excellent = no contact opening to 10 g or over.
A = very good = 6 to 10 g
B = good = 3.5 to 6 g
C = fair = 2 to 3.5 g
D = poor = 1 to 2 g
E = very poor = less than 1 g.

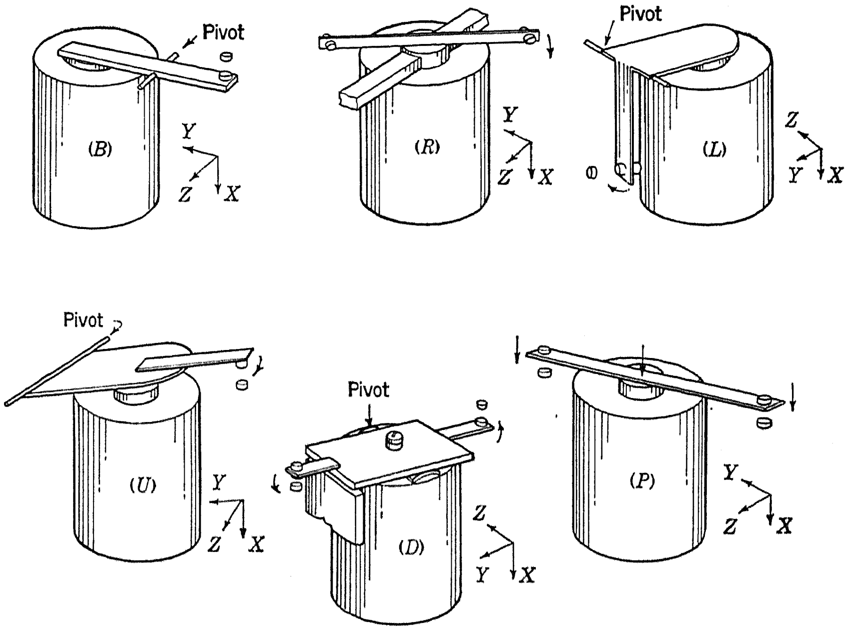


FIG. 13·30.—Relay armature and contact structures.

For the drop test the corresponding limits were:

X = more than 200 g
A = 75 to 200 g
B = 45 to 75 g
C = 25 to 45 g
D = 15 to 25 g
E = less than 15 g.

These limits were set up on the basis of military specifications for shock and vibration resistance rather than on the basis of what existing relays might be expected to stand. As will be seen from Fig. 13·31, the vibration test is comparatively easy to pass and the drop test is very severe.

In the case of the contact bounce and the single 200-g shock tests no

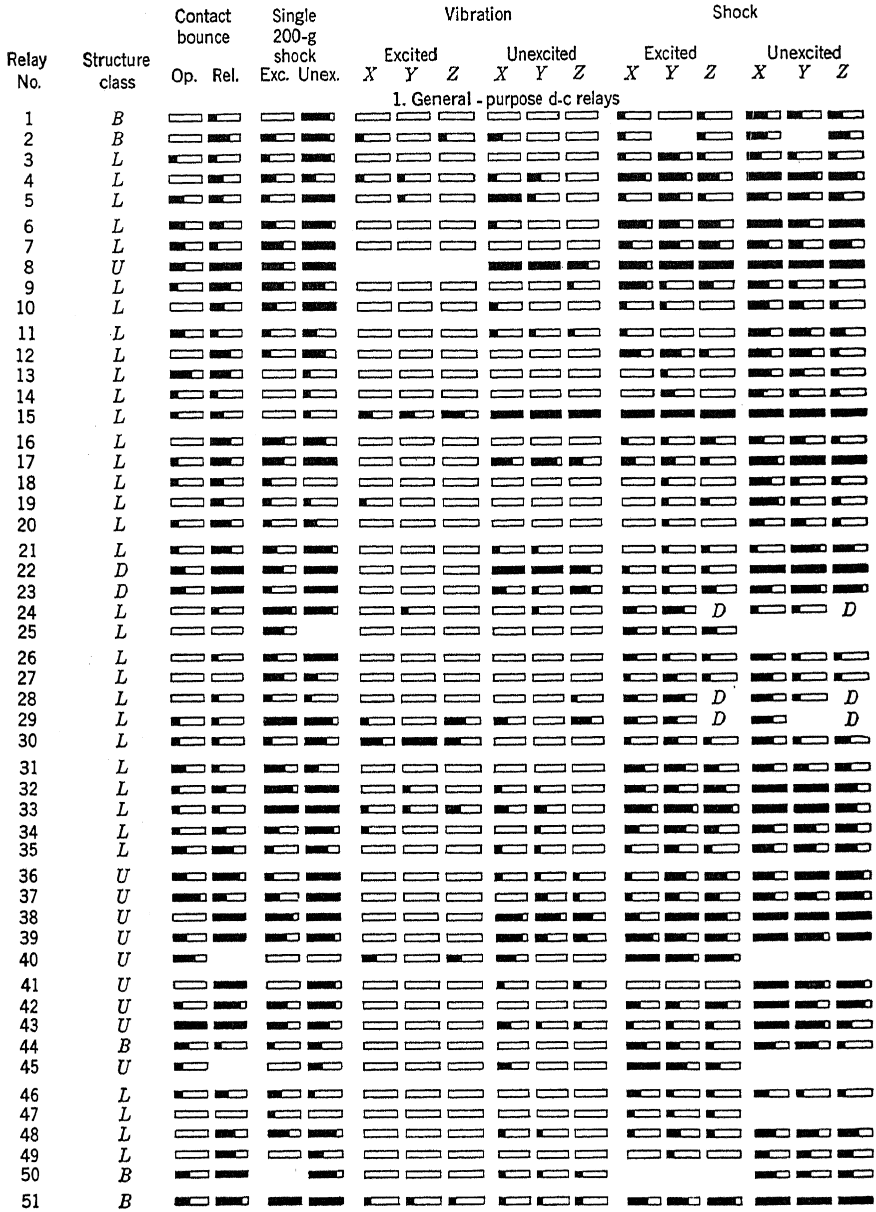
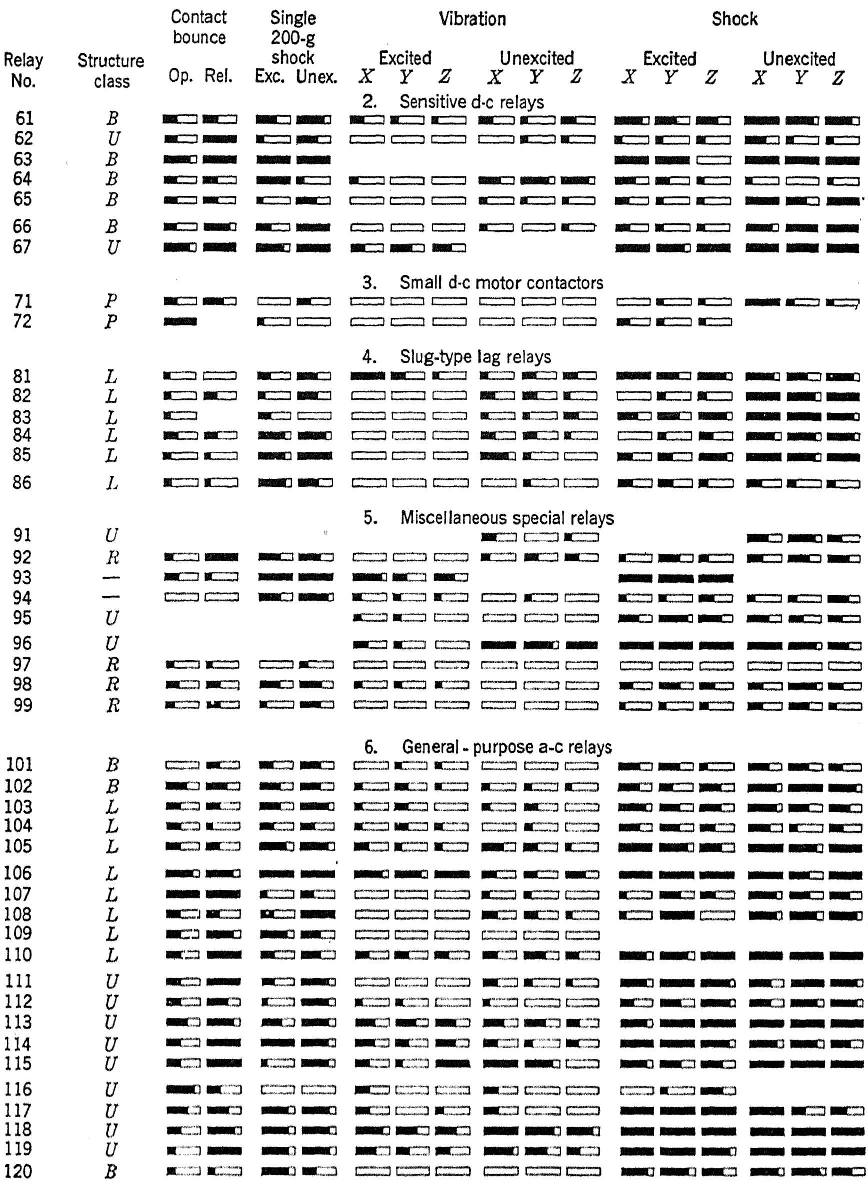


FIG. 13·31.—Relay shock, vibration,

quantitative data were available, so that the oscillograms of contact current were classified by visual inspection into six classes. The same six letters were used as before, X signifying either no effect or only a trace of "grass" on the oscillogram, while E signified severe, repeated,



and contact bounce characteristics.

and long-continued contact chatter. Such a method of grading is admittedly arbitrary, but it is believed to be fair as a comparative method.

In Fig. 13·31 each small rectangle represents the result of one test on one relay, the amount of blackening representing the result of the test.

Thus a white rectangle signifies a grade of X, a rectangle which is one-fifth black a grade of A, and so on to an all-black rectangle for E. Missing rectangles signify that the test data were lacking. The numbers of the rows are the relay numbers from Tables 13·1 through 13·6; the structure class letters refer to the sketches of Fig. 13·30.

Conclusions.—The first conclusion to be drawn from the mass of data presented in the tables and in Fig. 13·31 is that no evidence of outstanding superiority or inferiority can be found for any one make, construction, or class of relay. There are statistical differences, to be sure, but in view of the variability of relay characteristics with adjustment and other conditions the differences in the averages for the various classes are not particularly significant in most cases.

The data from the tables may be discussed first. The average temperature rise in Column 9 was 42.5°C for the 51 d-c relays of Table 13·1 and 48.5°C for the 20 a-c relays of Table 13·6. If all relays not tested at 125 per cent of rated voltage are omitted the figures become 46° and 48° respectively; in neither case is the difference very significant. Sensitive relays naturally run with very little temperature rise; the average 27° rise in Table 13·2 was caused by relatively enormous overexcitation. Slug-type lag relays tend to run hot because of their necessarily less efficient magnetic design and because long delay times require considerably greater than normal excitation.

The release factors of the d-c relays varied considerably; most of them lay between 20 and 60 per cent. The a-c relays naturally showed a much smaller spread; all were above 80 and two-thirds above 90 per cent.

Operate times of d-c relays at normal excitation varied from 6 to 80 msec, 80 per cent being below 30 msec. Release times were much more constant; 0.5 to 25 msec, with 80 per cent between 3 and 11 msec. Sensitive relays should theoretically be more sluggish than the normal type, but actually averaged about the same. A-c relays operated much faster than d-c relays (80 per cent between 4 and 11 msec) but released somewhat more slowly (80 per cent between 4 and 18 msec).

From the data of Fig. 13·31 certain conclusions are obvious and certain others can be tentatively drawn from a comparison of average scores. The scoring technique used was to express the score as the per cent of white space in all the rectangles of a given group, X scoring 100 per cent and E, 0 per cent. In comparing individual columns, contact bounce on release (38.6 per cent) is much worse than on operate (68.7 per cent). In all shock and vibration tests performance is worse with the coil unexcited than with it excited, the scores being for the single 200-g shock, 35.2 vs. 65.3 per cent; for the vibration test 78.9 vs. 88.0 per cent; and for the drop test 41.3 vs. 53.5 per cent. In the latter two tests the figures are average scores for the three directions in each case.

The differences in sensitivity to vibration and shock in the three directions are not striking except in the case of the drop test with the coil unexcited: here the scores are *X*, 27.7; *Y*, 37.2; and *Z*, 59.0 per cent. The *Z*-direction is also somewhat better in the other tests.

The vibration test is comparatively easy, scoring 83.4 per cent, while the other three tests averaged near 50 per cent. It might be noted that the vibration test used was that of the Navy, which is less severe than that of the Air Forces since it only employs frequencies up to 55 or 60 cps. If higher frequencies had been used it is probable that contact-spring resonance and similar effects would have caused a larger percentage of failures. The individual tests were of short duration also, and if time had permitted vibration life tests many more failures would have been caused by the loosening of screws, etc. This was demonstrated in the later tests on the Allied RMH and RLH relays, reported in Sec. 13·5.

Since most of the relays belonged to structure Class L, too few of any of the other classes were available to permit drawing conclusions as to the relative merit of the several classes. The shock resistance of the rotary relays was good, as was to be expected from their symmetrical form, and the plunger relays were good because of the large magnetic forces available in comparison with the inertial forces on the armature. Some of the relays that had been "shock-proofed" by adding counterweights to the armature were conspicuously bad.

No significant differences were seen between various classes of relays except that the a-c relays were much poorer than the others. This is to be expected in the excited condition, since the constantly repeated momentary weakening of the armature pull to a small value is not calculated to help the contacts to stay closed. It might be said that an a-c relay has its own vibration test built in. The inferiority of a-c relays with the coils unexcited is somewhat surprising, but may be due to the use of weaker armature springs, as indicated by the longer release times found for a-c relays. The a-c relays were tested just above the chatter point and the d-c just above drop-out, so the former were perhaps unduly penalized.

There were great differences in the performances of similar and even of supposedly identical relays, as well as a lack of sharp reproducibility of test results on any one relay. Numerical comparisons between individual models is therefore useless, and the diversity of constructions makes any kind of comparison difficult. Telephone-type relays seemed to be somewhat better than average in most respects, although this impression is not borne out by any significant difference in the scores. It was noted that relays with leaf-spring-mounted contacts did give more consistent and reproducible results in the tests. The superiority of

telephone-type relays, if it exists, may be due to their usually being made to more rigid specifications than other types.

In certain cases the shock tests resulted in permanent mechanical damage to the relays, often without opening the contacts. In the cases of Relays 24, 25, 27, 28 and 29 the armature was driven out of its pivots by shocks in the direction of the pivot axis, sometimes even by comparatively mild shocks. This is an inherent weakness of relays in which the armature is mounted between opposed cone-pointed screws rather than on an adequately captured through-pin.

The latching relays No's. 95 and 96 did not latch or unlatch under any of the shock or vibration tests; the open-circuiting was caused by vibration of the contact springs. The wafer-switch rotary relay, No. 97, successfully withstood all shock and vibration tests, either excited or unexcited.

The best score of any relay for which all tests were made was 96.7 per cent; the poorest was 16.2 per cent.

CHAPTER 14

RECEIVING TUBES

BY F. N. BARRY

14·1. Receiving Tubes.—This chapter will be devoted to a class of electronic tubes usually called "small tubes" or "receiving tubes." Neither term is particularly accurate as a class designation, but the latter will be used in the absence of anything better.

The decision as to whether a particular tube belongs to the class of receiving tubes or to some other class is often arbitrary, and in a number of the tables of the chapter tubes such as the 807 are included that would usually be considered transmitting tubes. Since they are often used in "receiving" equipment, however, it is felt that their inclusion is justified.

Considerations of space and time have made it necessary to eliminate a number of classes of tubes that could have been included in this chapter. The criterion for inclusion has been principally the importance of the class in the work of the Radiation Laboratory, and its application has led to the exclusion of filamentary-cathode tubes (except rectifiers and a few power tubes), acorn tubes, velocity-variation tubes (to which Vol. 7 of this series is devoted), and certain other classes. It has also led to the exclusion of various obsolete or obsolescent tubes, though this particular practice could have been carried considerably further.

The tables of this chapter are not intended to duplicate the tables of typical operating characteristics and other data which are to be found in numerous engineering handbooks and in the publications of the tube manufacturers. They are based primarily upon the information contained in Joint Army-Navy Specification JAN-1A for Radio Electron Tubes, and contain *limiting* and *test* values of various tube parameters rather than *typical operating* values. Much data, however, has also been obtained from the publications of the manufacturers, and some from tests made at the Radiation Laboratory.

The tabulated limits of essential characteristics are taken from JAN-1A and represent the values within which production tubes must remain in order to be acceptable to the Armed Forces. Tubes placed on the civilian market after the war may or may not be found to be within these limits, which are somewhat stringent in many cases, but the data as presented give an idea of the range of variation likely to be encountered. This matter will be discussed in greater detail in Secs. 14·3 and 14·4.

The maximum ratings given in both the tables and the text are "absolute maximum" unless otherwise specified. These values differ from the "design maximum" usually given by tube manufacturers, the latter normally being about 10 per cent lower than the "absolute maximum" values.

In all tables of characteristics the types which are underlined were on the Army-Navy preferred list of tubes dated Nov. 1, 1945. This list was set up because of the great number of tube types which differ in many cases only in some relatively unimportant detail such as mechanical structure or basing. In specifying a relatively limited number of types to be included in new equipment the problems of stock and supply are greatly simplified. The use of types included in this list often results in other advantages. The preferred types usually have characteristics which are superior, or at least not inferior, to those of similar nonpreferred types. Concentration by various manufacturers on large-scale production of a comparatively few types usually results in lower prices and more uniform characteristics. At least one manufacturer has been advocating a similar list for several years, with the same objective in mind.[1]

There will be cases, however, where a particular nonpreferred type has a special characteristic that makes it more suitable than any preferred type for a particular application, and in such cases, especially without the wartime necessity for standardization, the designer need not hesitate to specify the nonpreferred type.

In choosing a tube type for a new piece of equipment there are several general rules that may be observed with benefit:

1. With types that are made in both "G and "GT" styles the "G" style may be considered obsolescent. For example, use a 6H6GT or a metal 6H6 rather than a 6H6G. Many manufacturers have discontinued most of the "G" types and furnish tubes which are double-branded "GT/G"; the double-branding signifies that the tube will replace either the "G" or the "GT" type without circuit changes. Interelectrode capacitances may be somewhat different, however, often requiring retuning of i-f transformers, etc.
2. Tubes with a top-cap connection, except transmitting or high-voltage types or certain photocells, electrometer tubes, etc., may be considered obsolescent and similar single-ended types are to be preferred. For example use a 6SJ7 instead of a 6J7.
3. Types with the older bases (i. e., types that do not have octal, loctal, or miniature bases) are of older design and are usually inferior

[1] On Apr. 15, 1947, RCA issued a list, including some 82 receiving types, of tubes that are obsolete or nearly so and that designers are urged not to specify in the future. This is an excellent move and could well be made industry-wide.

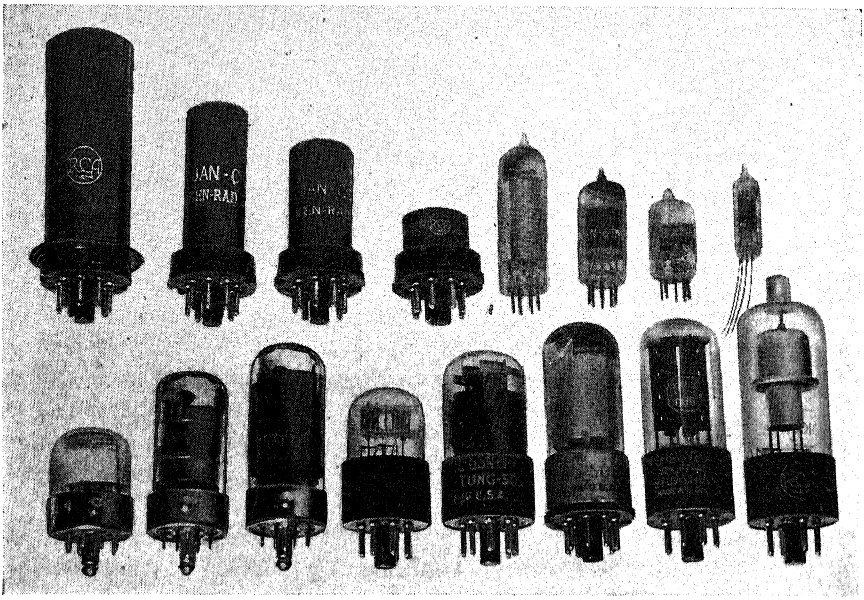
to some later type. Often an exactly similar tube may be found with a newer base: the 5Y3GT/G, a preferred and very widely used type, is electrically identical with the older type 80, but has an octal base and is made in a smaller bulb. This rule does not apply to most special-purpose and transmitting tubes; the 807 has a 5-pin base and the 2X2 a 4-pin base and top cap, but each is a highly desirable type in its class.

4. The choice between "loctal," "GT," or metal construction is largely a matter of individual preference and of which manufacturer is writing the advertising. Metal tubes have a psychological appeal to industrial users and others who stress the importance of mechanical ruggedness; they are better shielded than the glass types and have lower interelectrode capacitances but higher capacitance from some electrodes to ground and often poorer insulation. Loctal tubes have lower lead inductance and somewhat lower capacitances than tubes using a conventional stem construction, permitting them to be used at somewhat higher frequencies in many cases, but are much more prone than other types to contact trouble, since it is difficult to design a satisfactory socket contact for the hard small-diameter pins used in loctal and miniature tubes.
5. In recent years a number of miniature tubes have been announced. Most of these have 7-pin button bases and T-5½ bulbs, but lately a number of sub-miniature types in very small bulbs and with tinned leads, intended to be soldered into the circuits, have been developed. These small tubes save much valuable space and in many cases have additional advantages such as the ability to operate at high frequencies. A number of miniature and subminiature tubes are now in the developmental stage, and an increasing variety will be available in the future.

Physical Characteristics.—Receiving tubes range in size from the midget subminiatures, about ⅜ in. in diameter and 1½ in. long, or even smaller, to about 2 by 5¾ in. Figure 14·1 shows a number of small tubes in sizes from the subminiature SD834 to the large 6L6 in the MT-10 metal bulb and the 8016 in a T-9 bulb. Figure 14·2 shows tubes using the commoner sizes of ST-bulbs, from the ST-12 to the ST-16. Representative miniatures and subminiatures are shown in Figs. 14·3 and 14·4 and the construction of several individual types of tubes is shown in the cutaway drawings of later sections.

The requirements of electronic equipment for combat service have greatly accelerated two trends in the evolution of receiving tubes that were apparent before the war; the decrease in over-all dimensions and the increase in ruggedness. Both of these have various desirable by-products, and both merit a brief discussion.

(a) (b) (c) (d) (e) (f) (g) (h)



(i) (j) (k) (l) (m) (n) (o) (p)

Fig. 14·1.—Typical receiving tubes. (a) 6L6, RCA, Metal MT-10; (b) 6AG7, Ken-Rad, Metal MT-8; (c) 6AC7, Ken-Rad, Metal MT-8; (d) 6H6, RCA, Metal MT-8; (e) HD52, Hytron, long miniature T-5½; (f) 6C4, RCA, medium miniature T-5½; (g) 6AK5, WE, short miniature T-5½; (h) SD834, Sylvania, subminiature T-3; (i) 7F8, Sylvania, Loctal T-9; (j) 7H7, Sylvania, Loctal T-9; (k) 7N7, Sylvania, Loctal T-9; (l) 6H6GT/G, RCA, Octal T-9; (m) 6SN7GT, Tung-Sol, Octal T-9; (n) 6SJ7GT, Tung-Sol, Octal T-9; (o) 5Y3GT/G, Sylvania, Octal T-9; (p) 8016, RCA, Octal T-9 with top cap.

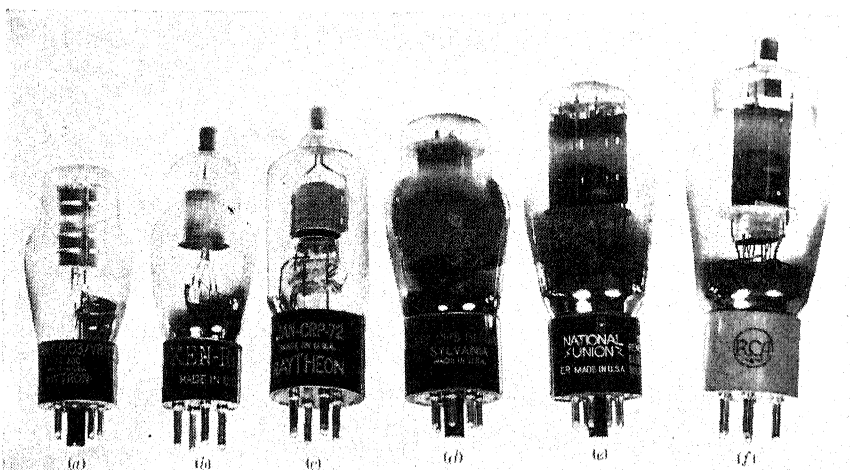


Fig. 14·2.—Typical large receiving tubes. (a) 0C3/VR105, Hytron, ST-12; (b) 2X2, Ken-Rad, ST-12 with top cap; (c) 72, Raytheon, T-12 with top cap; (d) 6L6GA, Sylvania, ST-14; (e) 6B4G, National Union, ST-16; (f) 807, RCA, ST-16 with top cap.

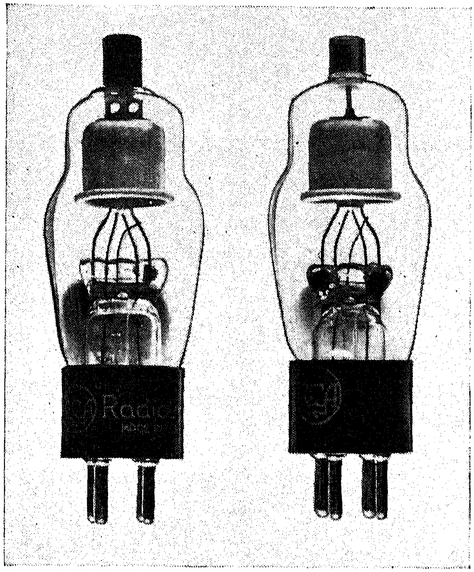
Several considerations have led to decreasing the over-all size of tubes, but the trend became apparent with the development of the acorn types in the '30's in an effort to secure higher-frequency operation by decreasing the lead inductance and interelectrode capacitance and increasing transconductance by the use of closely spaced elements. Acorn tubes were and are successful in attaining the results aimed at, but they are expensive to make and troublesome to mount, and the type of socket necessary occupies an excessive space. The next development was the loctal tube, which considerably reduced lead length and capacitance but which was not intended to save a great deal of space. The loctal tube, however, was successfully scaled down into the standard 7-pin miniature type,[1] and with this tube a real reduction in over-all size was realized. The miniatures were just beginning to make their mark before the war in small portable broadcast receivers, etc., and had in turn begotten a still smaller series of subminiatures which were principally used for hearing-aid amplifiers. The demands of the war greatly stimulated the production of miniature and subminiature types with low-drain filaments, both for walkie-talkies and other ultraportable equipment and for the proximity fuzes. The fuze tubes, which are still on the classified list, were produced in enormous quantities and are at present the *ne plus ultra* of compactness and ruggedness.

The demands for compact tubes capable of giving useful amplification at frequencies upwards of a hundred megacycles per second were met by a series of tubes of which the 6AK5 is typical. These were heater-type miniatures with very high transconductances and with short leads and fairly low capacitances. The miniature r-f amplifiers were accompanied by various other miniature heater-type tubes, notably several that were designed for operation at the low plate voltage of 28 volts, which can be obtained directly from the electrical systems of combat aircraft.

The trend to increased ruggedness in tube construction first became accelerated with the appearance of the metal tube. One of the hardest things to overcome in selling industrial electronic equipment is the assumption of the average buyer that a vacuum tube is delicate because it has a glass envelope, and one of the purposes of the metal tube was to assist in overcoming this prejudice. The advent of the metal tube stimulated the redesign of glass-envelope tubes for improved mechanical strength, and the military demands for tubes capable of withstanding very severe vibration and the shocks of gunfire have been answered by the production of "ruggedized" versions of several of the most-used (or most susceptible) tubes. These shock-resistant tubes usually have a suffix "W" in the type number: thus a 6L6WGA is a 6L6GA which is

[1] N. H. Green, "Miniature Tubes in War and Peace," *RCA Rev.*, **8**, 331–341 (June 1947).

electrically unchanged but is mechanically redesigned to have greatly increased shock and vibration resistance. Figure 14·3 shows standard and ruggedized versions of the 2X2. The present record in "ruggedization" is undoubtedly the proximity-fuze tubes, which must withstand linear



(*a*) (*b*)

Fig. 14·3.—"Ruggedized" and standard 2X2's. (*a*) Ruggedized (2B21); (*b*) standard 2X2.

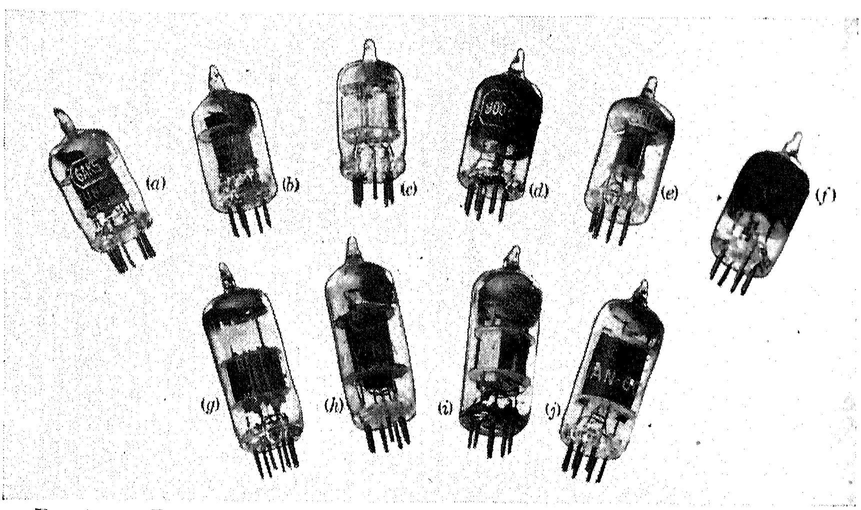


Fig. 14·4.—Typical miniature tubes. (*a*) 6AK5, Tung-Sol; (*b*) 6AS6, WE; (*c*) 6AL5, Hytron; (*d*) 9001, Ken-Rad; (*e*) 9002; (*f*) 9003, Ken-Rad; (*g*) 6J6, Raytheon; (*h*) 6D4, Sylvania; (*i*) 6AG5, RCA; (*j*) 6C4, RCA.

accelerations of tens of thousands of g while being fired from a gun, and also high centrifugal accelerations due to the rotation of the shell in flight.

Table 1 lists a number of acorn, miniature, and subminiature tubes, including various developmental types. An asterisk in the table signifies

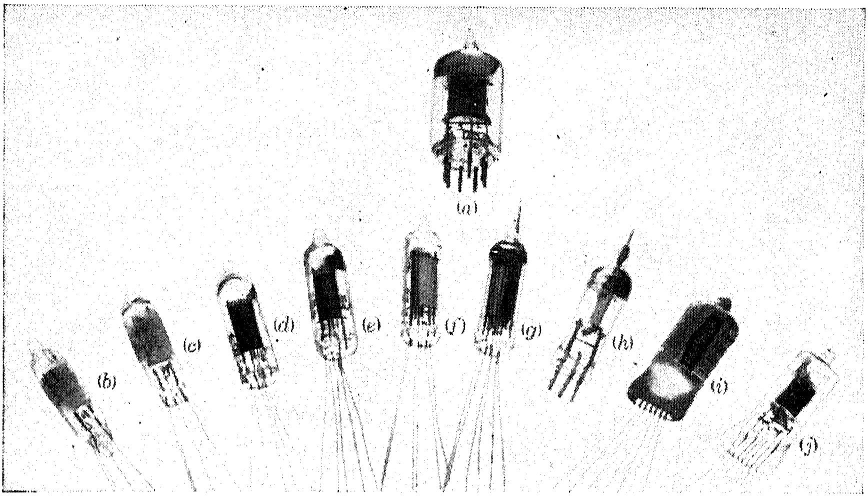


FIG. 14·5.—Typical subminiature tubes. (*a*) 6AK5, for comparison of size; (*b*) VW41, Victoreen; (*c*) VW32, Victoreen; (*d*) SD917, Sylvania; (*e*) SD834, Sylvania; (*f*) SD828A, Sylvania; (*g*) SD828E, Sylvania; (*h*) VR92 (British), Raytheon; (*i*) CK604A, Raytheon; (*j*) CK604A with conducting coating removed.

that the tube was a developmental type in 1946, when this chapter was written. Figures 14·4 and 14·5 show typical miniature and subminiature tubes. The only fairly common types of small tubes that are not represented in the figures are the acorn series.

Index of Types.—Tube types are arranged in the tables of characteristics according to function, structure, and characteristics and not according to type number. A cross index by type number is therefore given here as Table 2. Type numbers on the preferred list are underlined, and the references to the tables consist of the table and group numbers separated by a dash; thus the 6B4G has a reference of 10-3, which means it is to be found in Group 3 of Table 10. A particular tube may appear in more than one table; if so, references to each will be given, since cross references are not usually given in the tables of characteristics. A single asterisk following the type number signifies that the type is still in the developmental status at the time of compiling the tables. For convenience these developmental types have been listed separately in Table 3, together with the name of the manufacturer. Listing of a type, however, does not imply that it will necessarily become available on the market in the future.

TABLE 1.—ACORN, MINIATURE, AND SUBMINIATURE TUBES

Acorn Tubes	Group
Diodes	
9004	5-4
9005	5-3
Triodes	
6F4	12-8
REL36	12-13
955	12-13
Pentodes	
954	19-19
956	20-10
A4466B*	20-21
A4481A*	19-27
Miniature Tubes	
Diodes	
1A3	5-2
1Z2	9-5
2B25	9-14
6AL5	6-2
6AN6	6-5
6X4*	8-20
35W4	7-5
45Z3	7-3
117Z3	7-4
VC1017*	9-18
R1045-1*	9-16
R1045-4*	9-17
1654*	9-15
9006	5-6
Triodes	
6AQ6	15-7
6AT6	15-8
6C4	12-7
6J4	15-4
6J6	16-3
6N4*	15-19
12AT6	15-8
26C6*	15-17
A4442*	12-15
A4452*	12-16
9002	12-13
R-f Pentodes	
6AG5	19-17
6AJ5	19-14
6AK5	19-6
6AS6	19-11
6AU6	19-5

Miniature Tubes	Group
6BA6	20-3
12BA6	20-3
26A6*	20-22
A4444C*	20-20
A4464*	19-29
A4485*	19-27
9001	19-19
9003	20-10
Output and Transmitting Tubes	
2E30	23-1
6AK6	21-23
26A5*	21-24
HD34*	21-27
50B5	21-7
HD59*	23-1
A4450B*	21-25
A4455*	21-26
A4470*	21-26
Converters	
6BE6	27-3
12BE6	27-3
26D6*	27-5
Voltage Regulators	
OA2	31-7
OB2*	31-2
OC2*	31-5
HD52	31-2
Thyratrons	
2C4	32-5
2D21	33-1
6D4	32-4
GL546	33-2

Subminiature Tubes	Group
Diodes	
VR78	5-8
VR92	5-8
SC650*	5-11
R6271*	5-12
Triodes	
2C35*	15-21
6K4*	12-18
CK603*	15-22
SD834*	12-18
SD917*	15-20
R-f Pentodes	
CK602*	19-26
CK604A*	19-26
SD828A*	19-23
SD828E*	19-24

TABLE 2.—INDEX BY TYPE NUMBERS

Type	Group	Type	Group
OA2	31-7	3E29	25-3
OA3/VR75	31-2	5R4GY	8-8
OB2	31-5	5T4	8-6
OB3/VR90	31-3	5U4G	8-7
OC2	31-1	5V4G	8-5
OC3/VR105	31-6	5W4	8-1
OD3/VR150	31-8	5W4GT/G	8-1
1A3	5-2	5X4G	8-7
1B46	31-10	5Y3G	8-2
1B47	31-11	5Y3GT/G	8-2
1R4/1294	5-1	5Y4G	8-2
1-v	7-1	5Z3	8-7
1Z2	9-5	5Z4	8-3
2A3	10-3	6A3	10-3
2A4G	32-2	6A4/LA	21-21
2A5	11-8, 21-5	6A5G	10-3
2A6	15-12	6A6	16-1
2A7	26-1	6A7	26-1
2B7	20-18	6A8	26-1
2B25*	9-14	6A8G	26-1
2C4	32-5	6A8GT	26-1
2C21	13-1	6AB7	20-1
2C22	12-12	6AC7	17-3, 19-1
2C26A	12-5	6AC7W	19-1
2C34	13-2	6AD7G	11-8, 21-5
2C35*	15-21	6AG5	17-4, 19-7
2C40	15-1	6AG7	11-14, 14-3, 21-13
2C43	15-3	6AH7GT	13-3
2C48	10-7	6AJ5	19-14
2D21	33-1	6AJ7/6AC7	19-1
2E22	24-12	6AK5	17-2, 19-6
2E25	24-5	6AK6	11-13, 21-23
2E30	24-1	6AK7/6AG7	11-14, 21-13
2X2	9-2	6AL5	6-2
2X2A	9-2	6AN6	6-5
3B23	8-10	6AQ6	15-7
3B24	9-8	6AR6	21-2
3B24W	9-8	6AS6	19-11
3B26	9-4	6AS7G	10-8
3D21A	24-7	6AT6	15-8

TABLE 2.—INDEX BY TYPE NUMBERS (*Continued*)

Type	Group
6AU6	19-5
6B4G	10-3
6B6G	15-12
6B7	20-18
6B8	20-16
6B8G	20-18
6BA6	20-3
6BE6	27-3
6C4	12-7
6C5	12-19
6C5G	12-9
6C5GT/G	12-9
6C6	14-2, 19-22
6C8G	16-2
6D4	32-4
6D6	20-14
6D8G	26-2
6F4	12-8
6F5	15-14
6F5GT	15-14
6F6	11-8, 21-5
6F6G	11-8, 21-5
6F6GT	11-8, 21-5
6F8G	13-5
6G6G	11-13, 21-23
6H6	6-1
6H6G	6-1
6H6GT/G	6-1
6J4	15-4
6J5	12-11
6J5GT/G	12-11
6J6	16-3
6J7	14-2, 19-22
6J7G	14-2, 19-22
6J7GT	14-2, 19-22
6J8G	29-1
6K4*	12-18
6K5G	15-9
6K5GT	15-9
6K6GT/G	11-6, 21-9
6K7	20-15
6K7G	20-15
6K7GT	20-15
6K8	28-1
6K8G	28-1
6K8GT	28-1
6L5G	12-6
6L6	11-10, 21-1
6L6G	11-10, 21-1
6L6GA	11-10, 21-1
6L7	30-1
6L7G	30-1
6N4*	15-19
6N7	16-1
6N7G	16-1
6N7GT/G	16-1
6P5GT/G	12-2
6Q7	15-6
6Q7G	15-6
6Q7GT/G	15-6
6R7	12-4
6R7G	12-4
6R7GT/G	12-4
6S7	20-11
6S7G	20-11
6SA7	27-4
6SA7GT/G	27-4
6SB7Y	27-1
6SC7	16-6
6SC7GT	16-6
6SC7GTY	16-6
6SD7GT	20-4
6SF5	15-14
6SF5GT	15-14
6SF7	20-7
6SG7	20-2
6SG7GT	20-2
6SH7	17-1, 19-8
6SH7GT	17-1, 19-8
6SH7L	17-1, 19-8

TABLE 2.—INDEX BY TYPE NUMBERS (*Continued*)

Type	Group	Type	Group
6SJ7	14-1, 19-17	7B5	11-6, 21-9
6SJ7GT	14-1, 19-17	7B6	15-12
6SJ7Y	14-1, 19-17	7B7	20-12
6SK7	20-8	7B8	26-1
6SK7GT/G	20-8	7C4/1203A	5-7
6SL7GT	16-7	7C5	11-12, 21-4
6SL7W	16-7	7C6	15-11
6SN7GT	13-5	7C7	19-20
6SN7W	13-5	7E5/1201	15-2
6SQ7	15-12	7E6	12-4
6SQ7GT/G	15–12	7E7	20-17
6SR7	12-4	7F7	16-7
6SR7GT	12-4	7F8	16-4
6SS7	20-9	7G7/1232	19-9
6ST7	12-4	7G8/1206	22-4
6SU7GTY	16-7	7H7	20-5
6T7G	15-5	7J7	29-2
6U6GT	21-6	7K7	15-10
6U7G	20-14	7L7	19-13
6V6	11-12, 21-4	7N7	13-5
6V6G	11-12, 21-4	7Q7	27-2
6V6GT/G	11-12, 21-4	7R7	14-6
6W5G	8-14	7S7	29-3
6W7G	19-22	7V7	19-3
6X4	8-20	7W7	19-3
6X5	8-13	7X7	15-13
6X5G	8-13	7Y4	8-12
6X5GT/G	8-13	7Z4	8-15
6X5WGT	8-13	12A5	21-12
6Y6G	11-3, 21-8	12A6	11-11, 21-16
6Y7G	16-8	12A6GT	11-11, 21-16
6Z7G	16-9	12A8GT	26-1
6ZY5G	8-11	12AH7GT	13-3
7A4	12-11	12AT6	15-8
7A5	21-17	12BA6	20-3
7A6	6-3	12BE6	27-3
7A7	20-8	12C8	20-16
7A8	26-3	12F5GT	15-14
7AF7	13-4	12H6	6-1
7B4	15-14	12J5GT	12-11

TABLE 2.—INDEX BY TYPE NUMBERS (*Continued*)

Type	Group	Type	Group
12J7GT	14-2, 19-22	14F7	16-7
12K7GT	20-15	14H7	20-5
12K8	28-1	14J7	29-2
12K8Y	28-1	14N7	13-5
12L8GT	22-1	14Q7	27-2
12Q7GT	15-6	14R7	19-6
12SA7	27-4	14S7	29-3
12SA7GT/G	27-4	14W7	19-3
12SC7	16-6	14Y4	8-13
12SF5	15-14	15R	9-7
12SF5GT	15-14	RK25	23-8
12SF7	20-7	25A6	21-19
12SG7	20-2	25A6GT	21-19
12SH7	17-1, 19-8	25C6G	11-3, 21-3
12SH7GT	17-1, 19-8	25L6	11-7, 21-7
12SJ7	14-1, 19-17	25L6G	11-7, 21-7
12SJ7GT	14-1, 19-17	25L6GT/G	11-7, 21-7
12SK7	20-8	25Z5	8-18
12SK7GT/G	20-8	25Z6	8-18
12SL7GT	16-7	25Z6GT/G	8-18
12SN7GT	13-5	26A5*	21-24
12SQ7	15-12	26A6	20-22
12SQ7GT/G	15-12	26A7GT	11-1, 22-3
12SR7	12-4	26C6*	12-17
12SR7GT/G	12-4	26D6	27-5
12SW7	12-4	28D7	22-2
12SX7GT	13-5	28Z5	8-15
12SY7	27-4	HD34	21-27
12SY7GT	27-4	35A5	11-9, 21-11
12Z3	7-2	35L6GT/G	11-9, 21-11
14A4	12-11	35W4	7-5
14A5	21-16	35Y4	7-5
14A7/12B7	20-8	35Z3	7-5
14AF7	13-4	35Z4GT	7-5
14B6	15-12	35Z5GT/G	7-5
14B8	26-1	REL36	12-13
14C5	11-12, 21-4	38	21-18
14C7	19-18	39/44	20-19
14E6	12-4	41	21-9
14E7	20-17	42	11-8, 21-5

TABLE 2.—INDEX BY TYPE NUMBERS (*Continued*)

TABLE 2.—INDEX BY TYPE NUMBERS (*Continued*)

TABLE 3.—TUBES LISTED AS DEVELOPMENTAL IN THESE TABLES

The manufacturers of these tubes are under no obligation as to future production, if any, of these tubes.

Type	Manufacturer	Type	Manufacturer
OB2	Hytron	SD828E	Sylvania
OC2	Sylvania	SD834	Sylvania
2B25	Raytheon	S859 (OC2)	Sylvania
2C35	Raytheon	VC861	Sylvania
6K4	Sylvania	SR886	Sylvania
6N4	Raytheon	SD917	Sylvania
6X4	RCA (and others)	VC1017	National Union
26A5	RCA	R-1045-1	National Union
26A6	RCA	R-1045-4	National Union
26C6	RCA	M1060	National Union
26D6	RCA	1205	Sylvania
HD34	Hytron	1207	Sylvania
HD52 (OB2)	Hytron	1654	RCA
QK95	Raytheon	A4442	RCA
S491R	Sylvania	A4444C	RCA
CK602	Raytheon	A4450B	RCA
CK603	Raytheon	A4452	RCA
CK604A	Raytheon	A4455	RCA
SC650	Sylvania	A4464	RCA
SD673D (1205)	Sylvania	A4466B	RCA
Z694	KenRad	A4470	RCA
Z696	KenRad	A4481A	RCA
SD698C (1207)	Sylvania	A4485	RCA
SD705	Sylvania	R6271	RCA
SD828A	Sylvania	R6277 (6X4)	RCA

Notation.—The notation used in this chapter differs rather widely from that used in the remainder of the volume and of the series. It is based upon the notation of JAN-1A, which uses capitals for steady-state (d-c and rms) values and units and lower-case letters for instantaneous values of the same quantities, and which writes prefix and suffix letters on the same line with the main symbol instead of using subscripts. A brief list of symbols is given in Table 4, which does not contain all the symbols used in the tables but which does contain enough of them so that the others can be easily understood by analogy. A further variation from the standard practice of the rest of the book is the omission of the prefixed chapter number from the number of a table; thus the following table is numbered simply 4, and not 14·4. This is done in the interests of readability, since most of the remainder of this chapter is a continuous series of references to tables and it is not felt that prefixing each reference with an unnecessary 14 would serve any useful purpose.

TABLE 4.—SYMBOLS AND ABBREVIATIONS

A	Amperes, d-c or rms a-c.
a	Amperes, instantaneous or peak value. This usage is followed for other quantities such as voltage and power.
Avg	Average value.
C	Capacitance in micromicrofarads. Symbols are suffixed to the C to indicate between which electrodes the capacitance is measured, as Cgp, grid-to-plate capacitance. When the suffix becomes long or complicated a dash is inserted between the suffixed symbols, as C2g-1p, capacitance between the grid of Unit No. 2 and the plate of Unit No. 1 (of a twin triode, etc.)
Cin	Input capacitance, normally the capacitance from input grid to all other elements connected together.
Cout	Output capacitance, normally the capacitance from plate to all other elements connected together.
D	Diode element, or diode plate. If there is more than one a number is prefixed, as 1D, 2D. Prefixed numbers are also used with twin triodes, etc., to distinguish between sections.
e	Peak or instantaneous voltage.
eb	Peak d-c plate voltage.
Eb	D-c plate voltage (same as Ebb, the plate supply voltage, in the absence of external plate-circuit resistance.)
ecl	Peak grid No. 1 voltage
Ec	D-c grid voltage.
Ec2+4	D-c voltage of Grids 2 and 4 connected together, as in the screen of a pentagrid converter. Voltages of other elements or combinations of elements are indicated in the same way.
Ecc	D-c grid supply voltage (differs from Ec if grid current flows through an external resistor.)
Ef	Filament or heater voltage.
Ehk	Voltage between heater and cathode.
Epp	A-c plate supply voltage.
epx	Inverse peak plate voltage
epy	Forward peak plate voltage.
Etd	Average voltage drop between anode and cathode.
etd	Peak voltage drop between anode and cathode.
g, g1, etc.	Grids, numbering outward from grid closest to cathode as g1. Number of grid is omitted in case of triodes.
gm	Grid (or control grid, if other than triode) to plate transconductance in micromhos.
gm/section	Transconductance of one section of a twin tube. Other quantities for a twin tube are designated in the same way where necessary.
H	Heater-type cathode. Also may be used as a suffix, as -H, to designate hexode or heptode section of a converter.
hk or h-k	Heater to cathode.
i	Instantaneous or peak value of current. Used with modifying suffixes, as ib/p, peak current per plate of twin tube.
I	Steady-state (d-c or rms a-c) current in amperes. Used with modifying suffixes.
Ib	D-c component of plate current.
Ihk	Heater-to-cathode leakage current.
ik	Peak cathode current.

TABLE 4.—SYMBOLS AND ABBREVIATIONS (*Continued*)

Io	D-c output current of a rectifier
Is	Cathode emission current.
i surge	Instantaneous surge current.
kV	Kilovolts (d-c). Other prefixes such as m and μ are used in same way, as mAdc, milliamperes d-c.
max	Maximum
min	Minimum
Mu	Amplification factor.
nn	Refer to note for that tube type.
O	Oxide-coated filament.
p	Plate
P	Power dissipation rating; as Pg2, dissipation rating of Grid No. 2.
Pi	Total power input (to plate).
Rb, Rg, etc.	External circuit resistances.
rp	Plate resistance (dynamic).
RL	Plate or output load resistance.
Rp/Ib	Adjust Rp until Ib has specified value. Ec/Ib, etc., may be used in same way.
Sc	Conversion transconductance of a converter or mixer tube.
TC	Top cap.
T	As suffix, triode section of triode-hexode etc.
Th	Thoriated filament.
Tu	Pure tungsten filament.
tk	Cathode heating time, seconds, before plate voltage may be applied.
V	Volts d-c or rms a-c.
v	Instantaneous or peak volts.
W	Watts.
xx	Not applicable, as Ehk to a filamentary-cathode tube.

Additional symbols are used to denote the type of base, as 4, 5, 6, 7S and 7L for the old-style 4- to large 7-pin bases; Oct for standard octal; Loc for loctal or lock-in; Min for the miniature 7-pin button base; and Spec for special bases. Subminiature tubes ordinarily have no bases, and are denoted by SM. Lighthouse tubes, denoted by LH, usually have octal bases for the heater and d-c cathode connections. Bulb sizes are denoted by the RMA symbols except that the sizes of metal bulbs are not given. Ac means acorn tube. Top cap or caps are indicated after the basing symbol.

14·2. Diodes.—Diodes are most conveniently classified according to their intended applications. This section is concerned with three main classes of diodes: small single or multiple diodes such as are used for detection, clamping, etc.; medium-voltage medium-current rectifiers such as are commonly used in receiver plate supplies; and small low-current high-voltage rectifiers such as are most often used for CRT high-voltage supplies. The several other classes of diodes used for transmitter, X-ray tube, and battery-charging rectifiers, etc., will not be discussed.

Detectors.—The small diodes of Tables 5 and 6 are used primarily for the rectification of r-f currents in applications where the impressed voltages are moderate and the output current no greater than a few milliamperes, and where such characteristics as interelectrode capacitances and heater-to-cathode leakage are of primary importance. Single-section (half-wave) diodes are listed in Table 5; multiple diodes in Table 6.

Most of the types in Table 5 were designed for application at frequencies up to several hundred Mc/sec, and the requirements for operation at high frequencies (low capacitance, short lead length, and small electrode structure) has resulted in many cases in somewhat unusual constructions. Probably the extreme in this direction at present is the developmental type R6271, which uses the disk-seal "lighthouse" construction in a size small enough to fit the standard crystal-detector holder.

The individual columns of Tables 5 and 6 will now be discussed in order, the discussion of most of them being applicable also to the other tables of characteristics of this chapter.

The column headed "group" sets off into individual groups those types which have essentially the same electrical characteristics and differ only in heater voltage, basing, or some other relatively minor characteristic.

"Type" shows the type number of the tubes in the group. The list of type numbers is by no means complete, even within the limits set for this chapter, since in many cases a particular type may have been known by half a dozen different numbers at various times and places. The number given is usually either the RMA number or the manufacturer's number, which are commonly the same. In some cases a double number, such as 6A4/LA, is used for a tube which was simultaneously brought out by one manufacturer under one name and by another under another name. In a few cases also an equivalent number is added either in parentheses or in a footnote. Underlined types are those on the JAN preferred list.

The next two columns give the filament or heater voltage and current in volts and amperes. Nearly all of the tubes of this chapter have equipotential cathodes with the cathode sleeves insulated from the heaters; the exceptions are noted in the tables.

The next group of columns, entitled "maximum ratings," gives the characteristics of the tube which must never be exceeded if satisfactory operation and reasonably long life are to be obtained. As stated before, these are in most cases the "absolute maximum" values, and the "design maximum" values, which should be used in design work, are those usually given by the tube manufacturers and are somewhat lower. For Tables 5 and 6 the ratings given are the following:

epx Maximum inverse plate voltage, or the maximum instantaneous voltage across the diode when it is nonconducting.

ib Maximum instantaneous plate current, determined principally by the available cathode emission.

Io Maximum average cathode output current.

Ehk Maximum permissible potential between heater and cathode.

i surge Maximum momentary peak current at infrequent intervals such as warm-up periods. This is given in Table 6 only. The values of ib, Io, and i surge are per section for the tubes of Table 6, and are so denoted by the symbol /p.

The next group of columns shows the emission test data, which should not be confused with the Eb-Ib characteristic. Emission tests for all types of tubes are similarly made; all elements except the cathode are connected together and made positive by a voltage which is given in the Eb column; the limits of the resulting total emission current Is are given in the following columns. In the case of tubes with more than one set of electrodes, each set may be tested separately, as indicated by /p or /section.

The sixth and ninth groups of columns give the nominal interelectrode capacitances and the JAN acceptance limits of capacitance. Throughout this chapter all capacitances are given in micromicrofarads.

The next column gives the average emission current at Eb = 10 Vdc. This value is principally useful as a means of comparison; more complete information is available in the curves of Figs. 14·6 and 14·7.

The heater-cathode leakage test is made with the heater at 100 Vdc positive with respect to the cathode except as otherwise noted. It is a particularly important characteristic for the tubes of Tables 5 and 6.

The low-voltage test gives the limits of the plate current with zero external voltage applied. It is given for only a few types.

The next column gives the nominal resonant frequency in Mc/sec of each type with the shortest possible external leads.

The column headed "base" is really an indication of the kind of socket required since no indication is given of the type of base other than the pin arrangement. "Bulb" gives the RMA designation of the bulb size, except that the various sizes of metal bulbs are not distinguished.

The last column in each case gives numbers referring to footnotes concerning individual tubes or groups.

The principal considerations governing the choice of a diode for a particular application can be summarized fairly briefly. The single diodes of Table 5 are principally of interest at frequencies above those at which other types cease to be useful. The two lighthouse types 559 (5-10) and R6271 (5-12) are greatly superior to the others in frequency range, and the very small size of the latter and the relatively great power-handling capabilities of the former are also desirable in some cases. It is often possible to use modern point-contact crystal detectors such as the 1N21 and its various descendants, particularly the 1N34, in applications which would formerly have demanded a diode, and at frequencies above the range of the h-f diodes the crystals must be used.

The British VR 92 (5-8) has many desirable characteristics. It was

TABLE 5.—SMALL HALF-WAVE DIODES—FOR DETECTION, ETC.

Group	Type	Ef, V	If, A	Maximum ratings					Emission test			Nominal capacitances			Is mAdc Avg	Leakage, Ihk μAdc max.	Limits of capacitances						Fr, Mc/sec nom	Base	Bulb	Notes
				epx, V	ib, ma	Io, mAdc	Epp, Vac	Ehk, V	Eb Vdc	Is, mAdc Min.	Is, mAdc Max.	Cpk, μμf	Cph, μμf	Chk, μμf			Cpk, μμf Min.	Cpk, μμf Max.	Cph, μμf Min.	Cph, μμf Max.	Chk, μμf Min.	Chk, μμf Max.				
1	1R4/1294	1.4	0.15	365	......	1.0	130	50	..	....	...	0.36	....	...	2.5	20	....	....	....	...	...	...	....	Loc	T-9	(1)
2	1A3	1.4	0.15	365	5.5	0.55	...	100	10	0.8	...	0.4	0.8	0.6	2.0	20	0.2	0.6	0.6	1.0	0.4	0.8	1000	Min	T-5½	(2)
3	9005	3.6	0.165	365	......	1.0	130	−50	10	4.0	...	....	0.2	1.1	17	20	....	....	....	...	...	...	1500	Ac	Ac	(3)
4	9004	6.3	0.15	365	30	5.0	130	100	10	20.0	...	1.3	0.3	2.2	50	20	....	....	....	...	...	...	850	Ac	Ac	
5	380A	6.3	0.15	500	28.5	5.0	200	100	10	5.5	9.5	1.1	....	...	....	20	0.83	1.37	....	...	...	...	....	None	Spec	
	381A											1.4	....	...			1.05	1.75	....	...	...	...	....	Oct	Spec	
6	9006	6.3	0.15	825	16.5	5.5	...	100	20	13.0	...	1.4	0.2	2.2	6.5	20	0.8	2.0	0.05	0.6	1.2	4.2	700	Min	T-5½	
7	7C4/1203A	6.3	0.15	420	50.0	8.8	...	220	..	....	...	0.85	....	3.0	9.0	20	0.4	1.3	....	...	1.5	4.5	900	Loc	T-9	(4)
8	VR78	4.0	0.20	500	50.0	.....	...	....	10	34.0	...	1.35	0.45	2.4	....	20	....	2.0	....	1.0	...	4.0	....	SM	T-4	(5)
	VR92	6.3	0.15																							
9	704A	4.5	0.48	...	200	10.0	...	....	10	3.0	8.0	0.7	....	...	....	..	0.55	0.85	....	...	...	...	....	None	Spec	(6)
10	559	6.3	0.75	...	1000	30.0	...	....	5	24 Av.		2.65	....	...	65	..	2.1	3.2	....	...	...	...	....	LH	LH	
	Developmental types																									
11	SC650	6.3	0.15	...	......	......	...	....	..	....	...	....	....	...	9.0	..	....	....	....	...	...	...	....	SM	T-4	
12	R6271	6.3	0.30	200	......	25.0	...	....	1	25 Av.		3.5	....	...	....	..	....	....	....	...	...	...	....	Spec	Spec	(7)

NOTE: The emission current Is at 10 Vdc may exceed the maximum rating of the tube but is shown as a basis of comparison between types.
The leakage test is made with Ehk 100 Vdc except as noted.
(1) Cp-hk = 2.5 μμf max. Ehk = 50 Vdc for leakage test. Cp—all others = 1.6 μμf nominal.
(2) Ef = 1.1 V for emission test.
(3) Cp-hk = 0.45 μμf min., 0.85 max.
(4) Cp—all others = 2.2 μμf nominal.
(5) Subminiatures with short rigid tinned leads, plate lead out of top. Have test for very low values of Eb: Eb = −1.0 Vdc, Ib = 5 μAdc max.; Eb = −0.2 Vdc, Ib = 5 μAdc min.
(6) Cathode tied internally to one heater lead.
(7) Very small subminiature lighthouse, same dimensions as standard crystal rectifier.

TABLE 6.—SMALL MULTIPLE DIODES—FOR DETECTION, ETC.

Group	Type	Ef, V	If, A	Maximum ratings					Emission test		Nominal capacitances			Is/p, mAdc Av.	Leakage, Ihk, μAdc max.	Capacitance limits				Low-voltage test Ebb = 0 Vdc			Base	Bulb	Notes
				epx, v	ib/p, mA	Ic/p, mAdc	i surge/p, mAdc	Ehk, V	Eb, Vdc	Is/p, mAdc min	C1p—all except 2p, 2k, μμf	C2p—all except 1p, 1k, μμf	C1p-2p max., μμf			C1p—all except 2p, 2k, μμf		C2p—all except 1p, 1k, μμf		RL, ohms	Ib, μAdc				
																Min.	Max.	Min.	Max.		Min	Max.			
1	6H6	6.3	0.30	465	50	8.8	176	360	20	15	3.0	3.5	0.10	12	5	2.2	3.8	2.5	4.5	34,000	4	25	Cct	Metal	(1)
	6H6G										3.2	4.0	0.10			2.0	4.5	3.0	5.0				Oct	ST-12	
	6H6GT/G										3.0	4.0	0.10										Oct	T-9	
	12H6	12.6	0.15								3.0	3.5	0.10		20	2.2	3.8	2.5	4.5				Oct	Metal	
2	6AL5	6.3	0.30	460	60	10.0	350	360	10	40	3.0	3.0	0.026	65	20	2.3	3.7	2.3	3.7	40,000	5	20	Min	T-5½	(1), (2)
3	7A6	6.3	0.15	465	50	8.8	176	360	20	15	...	...	0.10	14	20	...	...	...	...	......	..	..	Loc	T-9	(1), (5)
4	Typical diode in "duc-diode triode," etc.			...	..	1.0	...	...	10	0.8	...	...	.....	2.0	..	...	...	...	...	......	..	..	....	.....	(3)
5	6AN6	6.3	0.20	210	10	3.3	33	100	10	2.5	...	...	.....	.....	20	...	...	...	...	......	..	..	Min	T-5½	(4)

NOTES: Ehk = 100 Vdc for leakage test. Test at Ebb = 0 is per section for 6AL5; for both sections for group 1. Leakage test is per section.

(1) Two independent diode sections in same envelope.

(2) C1k—all except 2k, 2p = 2.8 μμf min, 4.0 max.
C2k—all except 1k, 1p = 2.8 μμf min, 4.0 max.
Nominal resonant frequency is 700 Mc/sec.

(3) Cathode common with triode or pentode section in same envelope; for further data see Tables 12, 15, and 20.

(4) Four plates and common cathode.

(5) C1p-1k = 2.0 μμf average; C2p-2k = 2.6 μμf average.

manufactured in quantity in this country during the war, but it may not be easily obtained in the future. Since it has no base it is ordinarily soldered into the circuit like most other subminiatures, although it is exceptional in having short rigid tinned leads that might be successfully held in clips.

Of the more conventional multiple diodes, those of groups 6-1 and 6-2 are the most widely used because of their high Ehk ratings, low-voltage specifications, moderately low capacitances, and low cost resulting from volume production. The 7A6 (6-3) is approximately equivalent to 6-1 and 6-2 but does not have as complete specifications. The 6AL5 (6-2) has a particularly low forward resistance, which is desirable for some clamping-circuit applications. The VR-92 also has a low forward resistance. The 6AN6 (6-5) is a miniature quadruple diode, but for many applications its use of a common cathode for all sections is a disadvantage. This disadvantage is shared by practically all the tubes grouped under 6-4, which applies to a typical diode section of a duo-diode triode or duo-diode pentode such as is used for the second detector and first audio stage of most broadcast receivers. The diode sections of practically all of these tubes are similar, but are good for little else than their intended use because of their common cathodes and their excessive forward resistance.

Figure 14·6 shows the Eb-Ib Characteristics of a number of detector diodes. These characteristics are slightly idealized by assuming that they all follow a three-halves-power law of Ib vs. Eb. This assumption is reasonably accurate in most cases if the origin of the voltage scale is taken not at zero impressed voltage but at some point usually about one-half volt negative, which is approximately the point of zero virtual current. Unless this point is taken as the origin, the characteristics will not give straight lines on log-log paper.

Figure 14·6 also gives the characteristics of several diode-connected triodes and pentodes. These tubes are often used as diodes either to reduce the number of tube types in a given piece of equipment or because a few such tubes have lower forward resistances than any of the regular detector diodes. An excellent example is the 6AC7. A power rectifier diode may be used occasionally because of its higher current rating, but the 6AL5 has a lower resistance at low currents than any of the power diodes.

To summarize for all except very high frequencies, the 6H6 is a popular but rather poor diode with separate cathodes, much used for amplitude selection and detection of c-w and video signals. The 6AL5 is a far better miniature version of the 6H6 with very low rp and Cpk; it is the best low-power diode for general use in i-f and pulse circuits. The VR-92 is essentially half of a 6AL5, and is useful up to fairly high frequencies.

Plate-supply Rectifiers.—The tubes of Tables 7 and 8 are used primarily for power rectification for outputs up to several hundred volts. The various columns of the tables indicate nearly the same characteristics as those of Tables 5 and 6. For power-supply purposes such characteristics as capacitances, heater-to-cathode leakage, etc., are unimportant and are not usually given, so that these columns have been omitted from

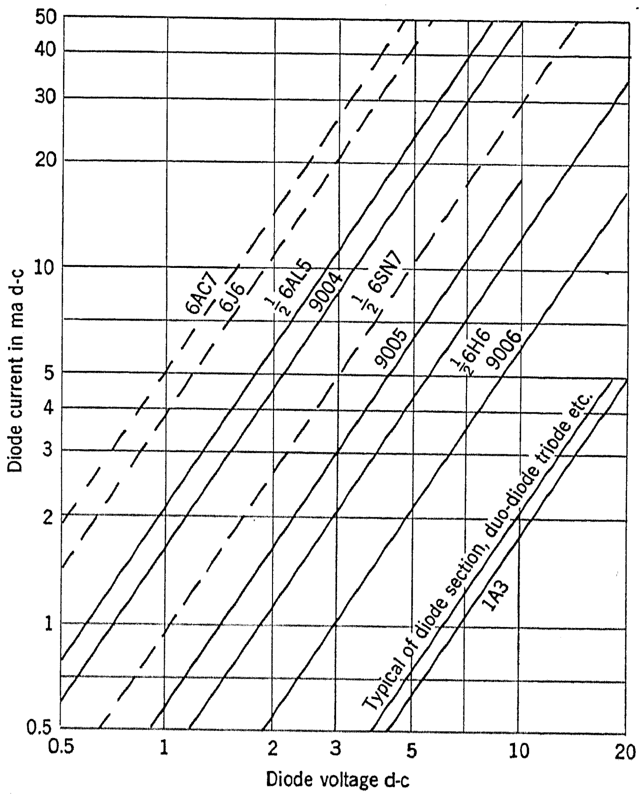


FIG. 14·6.—Characteristics of small diodes. Diode voltage = externally applied positive voltage plus negative voltage at which diode first conducts, sometimes called "contact potential." Dashed lines are for diode-connected triodes or pentodes.

Tables 7 and 8. An additional column in Table 8 indicates the type of cathode, since many of the more important power rectifiers have filamentary cathodes.

Table 7 lists half-wave high-vacuum power rectifiers, arranged in order of increasing maximum output currents. These tubes are widely used in transformerless (a-c–d-c) home radio receivers but find little application elsewhere. None is on the JAN preferred list; this indicates not that they are unsuited for military applications but that the Services frowned upon transformerless power supplies.

TABLE 7.—SMALL HALF-WAVE PLATE-SUPPLY DIODES

Group	Type	Ef, V	If, A	Maximum ratings: epx, v	ib, ma	Io, mAdc	i surge, a	Ehk, V	Emission test: Eb, Vdc	Is, mAdc Min.	Is, mAdc Max.	Is mAdc Avg	Base	Bulb	Notes
1	1-v	6.3	0.30	1000	300	50	1.0	500	20	60	. . .	65	4	ST-12	
2	12Z3	12.6	0.30	750	360	60	1.2	365	30	200	. . .	140	4	ST-12	
3	45Z3	45	0.075	385	430	72	. . .	200	30	100	270	110	Min	T-5½	
4	117Z3	117	0.04	365	600	100	2.0	175	30	250	. . .	. . .	Min	T-5½	
	117Z4GT												Oct	T-9	
5	35Z3	35	0.15	365	660	110	1.1	350	30	200	. . .	250	Loc	T-9	(1)
	35Z4GT/G						2.2			250	. . .		Oct	T-9	
	35Y4						. . .			. . .	. . .		Loc	T-9	
	35W4												Min	T-5½	
	35Z5GT/G						2.2			250	. . .		Oct	T-9	
	45Z5GT	45	0.15									275			(1), (2)

NOTES: (1) Types in this group, except the 35W4, may be operated with epx = 700 v provided the circuit contains a minimum plate-supply impedance of 100 ohms.
(2) Has heater tap for dial lamp.
Eb = 20 Vdc for average Is values given.

Table 8, listing full-wave power rectifiers, is divided into three sections. Tubes of Groups 8-1 to 8-10 are primarily intended for a-c power supplies with conventional center-tapped transformer secondaries, as distinguished from vibrator and voltage-doubler circuits. Tubes suitable also for vibrator circuits are included in Groups 8-11 to 8-16, and voltage-doubler tubes in Groups 8-17 to 8-19. Within each section tubes are arranged in order of increasing output current.

The tubes of Table 7 require little comment and will not be discussed here. Those of the first section of Table 8 all have either filamentary cathodes or equipotential cathodes which are internally connected to the heater. In general they may be divided into two classes, those which have a close-spaced cathode-plate structure with a resultant low voltage drop, and those which have a wider spacing and a higher drop. All of the close-spaced tubes (Groups 8-3 and 8-5 and the 5V4G, 83V, and 5Z4) have heater-type cathodes. The 5T4, which has a filamentary cathode, is intermediate in characteristics between the two classes. The close-spaced tubes offer the advantages of lower tube drop, higher efficiency, and better voltage regulation, approaching the characteristics of mercury-vapor rectifiers. Their disadvantages are that they offer little protection either to themselves or to the transformer in case of a short-circuit across the output, and both may be destroyed unless properly fused. It is commonly believed also that they are less rugged and more prone to develop internal short-circuits than the wide-spaced tubes. None is on the JAN preferred list.

Of the wide-spaced tubes the 5Y3GT/G and the 5U4G are both widely used, the latter having a high output-current rating and the former a smaller physical size and lower filament power, which is advantageous when output current requirements are within its ratings. The 5R4GY has a considerably higher voltage rating than either of the two previous types, and a fairly high current rating.

The 1641 and the 3B23 are really small transmitting rectifiers but were included in the table since they are the only common types of full-wave high-vacuum transmitting rectifiers and since they differ only in degree from the other tubes in the table.

The Eb-Ib characteristics for many of the tubes in Table 8 are given in Fig. 14·7, which is similar to Fig. 14·6 for the detector-type diodes.

The tubes of Groups 8-11 to 8-16 were intended to be used in vibrator-type power supplies as well as for a-c supplies. All of them have separate heaters with high heater-to-cathode voltage ratings. None has separate cathodes for the two sections, however. The largest of them has a lower maximum output current rating than even the smallest of the previous section. All except the 7Z4 and 28Z5 of group 8-15 are of close-spaced construction. The 6X5GT is probably the most widely used, although

TABLE 8.—FULL-WAVE PLATE-SUPPLY DIODES

Group	Type	Ef, V	If, A	Maximum ratings: epx, v	Maximum ratings: ib, mAdc	Maximum ratings: Io, mAdc	Maximum ratings: i surge, a	Maximum ratings: Ehk, Vdc	Emission test: Eb, Vdc	Emission test: Is/p, mAdc Min.	Emission test: Is/p, mAdc Max.	Is/p, mAdc Avg	Cathode type	Base	Bulb	Notes
1	5W4	5.0	1.5	1550	330	110	1.1	xx	75	120	...	30	O	Oct	Metal	
	5W4GT													Oct	T-9	
2	5Y3G	5.0	2.0	1550	415	140	1.4	xx	75	120	...	25	O	Oct	ST-14	
	5Y3GT/G													Oct	T-9	
	5Y4G													Oct	ST-14	
	80													4	ST-14	
3	5Z4	5.0	2.0	1550	415	140	1.4	xx	50	300	...	120	H	Oct	Metal	(1)
4	274A	5.0	2.0	1650	525	175	1.75	xx	60	135	200	...	O	4	ST-16	
	274B													Oct	ST-16	
5	5V4G	5.0	2.0	1550	575	190	1.9	xx	30	185	...	140	H	Oct	ST-14	(1)
	83V													4	ST-14	
6	5T4	5.0	2.0	1700	750	250	2.5	xx	75	300	...	70	O	Oct	Metal	
7	5U4G	5.0	3.0	1700	750	250	2.5	xx	75	225	...	45	O	Oct	ST-16	
	5X4G													Oct	ST-16	
	5Z3													4	ST-16	
8	5R4GY			3050	700	0	....	xx	75	225	375	45	O	Oct	ST-16	(2)
		.....		2800		165										(2), (4)
		5.0	2.0	2900		190										(3), (4)
				2300		275										(3), (4)
				2150		275										(2), (4)
9	1641	5.0	3.0	4500	165	55	....	xx	75	225	...	...	O	4, 2TC	ST-16	(2)
				2300	825	275	2.75									(2)
				2750	360	275	....									(3)
10	3B23	2.5	8.0	3500	600	200	....	xx	25	184	...	...	H	4, 2TC	S-19	(1), (5)

11	6ZY5G	6.3	0.3	1375	130	44	0.45	450	30	45	. . .	48	H	Oct	ST-12	(6)
12	7Y4	6.3	0.5	1375	200	65	0.65	450	30	75	. . .	65	H	Loc	T-9	(6)
	84/6Z4								25	60	. . .			5	ST-12	
13	6X5	6.3	0.6	1375	230	75	0.75	450	50	140	. . .	65	H	Oct	Metal	(6)
	6X5G													Oct	ST-12	
	6X5GT/G													Oct	T-9	
	6X5WGT													Oct	T-9	(6), (7)
	14Y4	12.6	0.3						30	80	. . .			Loc	T-9	(6)
14	6W5G	6.3	0.9	1375	300	100	1.0	450	50	150	. . .	70	H	Oct	ST-12	(6)
15	7Z4	6.3	0.9	1375	330	110	1.1	450	50	80	. . .	37	H	Loc	T-9	
	28Z5	28.0	0.24													(9)
16	345A	6.3	1.0	1375	330	110	1.1	450	15	55	95	. . .	H	5	ST-12	(6)
17	117Z6GT	117	0.075	730	400	66	1.35	385	30	150	. . .	175	H	Oct	T-9	(8), (10)
18	25Z5	25.0	0.3	730	500	85	1.65	385	30	170	. . .	140	H	6	ST-12	(8), (10)
	25Z6													Oct	Metal	
	25Z6GT/G													Oct	T-9	
19	50Y6GT/G	50	0.15	365	500	85	1.65	330	30	170	. . .	140	H	Oct	T-9	(8), (10)
				Developmental types												
20	6X4 (R6277)	6.3	0.60	Ratings and characteristics similar to 6X5									H	Min	T-5½	(6)
21	SR886	117	. . . .	Ratings and characteristics similar to 117Z6GT									H	Loc	T-9	(8)

NOTES: (1) Cathode internally connected to one side of heater.
(2) With choke-input filter.
(3) With condenser-input filter.
(4) Filament must be preheated for 10 sec before application of plate voltage for these ratings. This is not necessary for somewhat lower applied voltages.
(5) Filament preheating time 30 sec.
(6) Cathode common to both sections.
(7) Ruggedized.
(8) Separate cathodes. May be used in voltage-doubler circuits.
(9) Heater is center-tapped; may be operated at 0.48 amp and 14.0 volts.
(10) Values for ib and Io are per plate.
Average Is/p is determined at Eb = 20 Vdc.

Groups 8-15 and 8-16 are useful if higher output currents are required. The developmental 6X4 is a miniature equivalent of the 6X5GT and is the only miniature of this type in the table.

The tubes of Groups 8-17 to 8-19 are intended primarily for transformerless power supplies and are suitable for use in voltage-doubling

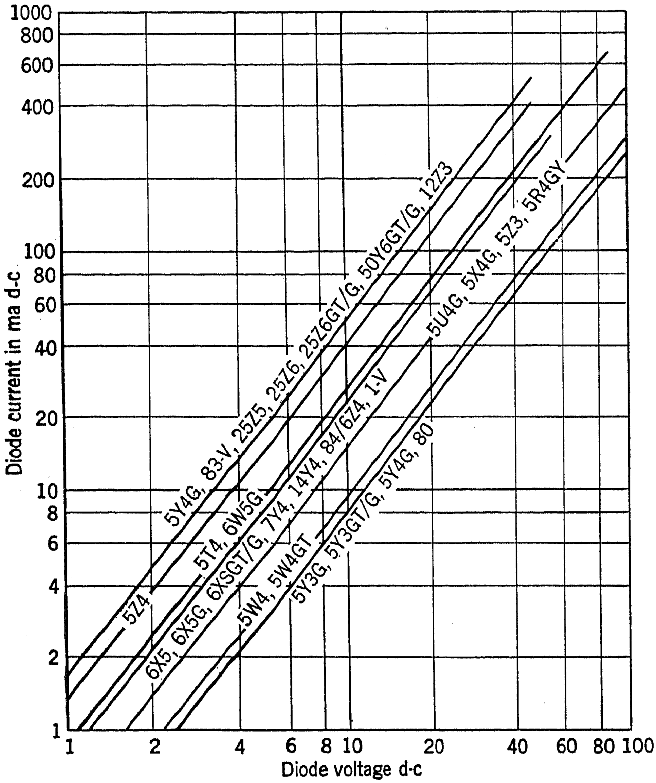


FIG. 14·7.—Characteristics of small plate-supply diodes. Diode voltage = externally applied positive voltage plus negative voltage at which diode first conducts.

circuits. All are of close-spaced construction and have separate cathodes and fairly high heater-to-cathode voltage ratings.

Not shown in the tables are the full-wave mercury-vapor rectifiers. There are only two of these; the 82, which is obsolescent, and the 83, which is essentially a mercury-vapor 5Z3. The latter is on the JAN preferred list.

To summarize the power-supply rectifiers, the 5Y3GT/G is a useful general-purpose rectifier for power supplies furnishing up to about 125 ma at 400 volts, the 5U4G up to 600 volts and 250 ma, and the 5R4GY for still higher voltages. The 6X5 is useful in small power supplies in which

the heater must be grounded, and is commonly employed in negative bias supplies. It is also useful as a diode switch since it has a low impedance and is very reproducible in manufacture. It can be used in precision modulation and demodulation.

High-voltage Rectifiers.—The third general class of diodes discussed in this chapter consists of the types intended to supply currents of a few

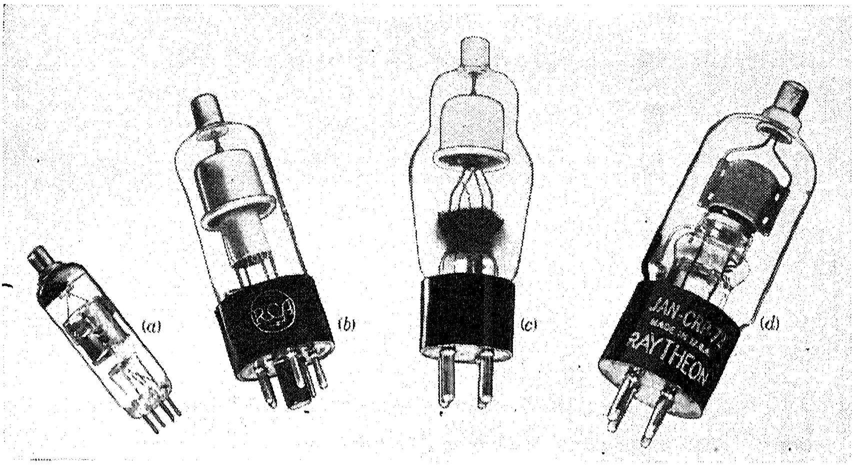


FIG. 14·8.—Typical high-voltage rectifier tubes. (*a*) 1Z2, National Union; (*b*) 8016, RCA; (*c*) 2X2, RCA; (*d*) 72, Raytheon.

milliamperes at several kilovolts, and are most commonly used in cathode-ray-tube high-voltage supplies. Since there is no sharp division between these types and the somewhat larger types, however, a few of the latter are included. All except one developmental type have the plate connected to a top cap in order to increase the voltage rating. All have rather high internal voltage drops, but this is of minor importance since the current is small and the drop is a very small fraction of the output voltage. They are listed in Table 9.

The 2X2 and 2X2A are the most widely used tubes of this class. The 1Z2, which has only recently reached the market, also has considerable value in low-current high-voltage applications.

Four typical high-voltage diodes are shown in Fig. 14·8. In connection both with high-voltage rectifiers and power-supply rectifiers, it should be pointed out that high-voltage selenium rectifier stacks are beginning to make appreciable inroads on the market for rectifier tubes. Selenium rectifiers are still much more expensive than most tubes, but they have numerous advantages, particularly in the absence of a requirement for filament or heater power, and in their long life, which makes practicable the construction of self-contained transformer-rectifier-filter units such as those described in Chapter 4 of this volume.

TABLE 9.—HALF-WAVE HIGH-VOLTAGE RECTIFIERS

Group	Type	Ef, V	If, A	Maximum ratings					Emission test			Is mAdc Avg	Cathode type	Base	Bulb	Notes
				epx, kv	ib, mAdc	Io, mAdc	i surge, ma	Pp, W	Eb, Vdc	Is, mAdc Min.	Is, mAdc Max.					
1	8016	1.25	0.20	10.0	7.5	2.0	....	..	100	2.5	8.0	4	O	Oct	T-9	
2	2X2	2.50	1.75	12.5	45.0	7.5	100	..	200	30	65	17	H	4	ST-12	
	2X2A															(4)
3	73	2.50	4.25	13.0	3000	30	....	..	130	100	.....	..	O	Oct	T-9	(1)
4	3B26	2.50	4.75	15.0	8000	20	....	..	130	100	.....	..	H	Oct	T-9	(1)
5	1Z2	1.50	0.30	20.0	10	2	....	..	...	.....	.....	14	Th	Min	T-5½	
6	72	2.50	3.00	20.0	100	20	....	..	200	70	140	..	Th	4	T-12	
7	15R	5.00	3.90	20.0	150	30	1200	..	200	120	180	..	Th	Spec	Spec	
8	3B24	2.5/5.0	3.00	20.0	150/300	30/60	....	..	250	100	.....	..	Th	4	T-12	(2), (3)
	3B24W															(2), (3), (4)
9	953B	7.50	6.00	30.0	80	40	....	..	200	80	.....	..	Tu	....	......	
10	705A	5.00	5.00	30.0	400	100	....	60	300	290	440	..	Th	Spec	Spec	
				15.0	600	150										
11	8013A	2.50	5.00	40.0	150	20	200	..	300	33	59	10	Th	4	T-16	
12	8020	5.00	6.00	40.0	750	100	....	75	200	75	.....	..	Th	4	T-19	
13	100R	5.00	6.20	40.0	750	100	2000	75	200	75	.....	..	Th	4	T-19	

TABLE 9.—HALF-WAVE HIGH-VOLTAGE RECTIFIERS.—(*Continued*)

Group	Type	Ef, V	If, A	Maximum ratings					Emission test			Is mAdc Avg	Cathode type	Base	Bulb	Notes
				epx, kv	ib, mAdc	Io, mAdc	i surge, ma	Pp, W	Eb, Vdc	Is, mAdc Min.	Is, mAdc Max.					
Developmental types																
14	2B25	1.40	0.11	2.8	......	2	....	..	60	4 Avg		..	..	Min	T-5½	
15	1654	1.40	0.05	100 μAdc at 5 kVdc								..	O	Min	T-5½	
16	R1045-1	6.3	0.30	2 mAdc at 10 kVdc								..	..	Min	T-5½	
17	R1045-4	6.3	0.15	20 mAdc at 2 kVdc								..	..	Min	T-5½	
18	VC1017	6.3	0.15	Miniature equivalent of 2X2								..	..	Min	T-5½	
19	QK95	....	....	Improved 3B26									..	....	......	
20	VC861	....	....	epx = 15 kv, Ib = 50 to 60 mAdc.								..	..	....	......	

NOTES: All the tubes listed have top-cap plate connection except the 2B25.
Not listed are the 2V3G and 878 (obsolescent types) and the VU-111 (British).
Average values of Is are for Eb = 100 Vdc.
(1) 73 and 3B26 are clipper diodes.
(2) Filament has two halves; either or both may be used. Lower current ratings apply to operation with half of the filament lighted.
(3) Emission test is made with both halves of filament lighted.
(4) Ruggedized type.

TABLE 10.—LOW-MU TRIODES

Group	Type	Ef, V	If, A	Max. ratings: Eb, Vdc	Max. ratings: Pp, W	Max. ratings: Ehk, Vdc	Test conditions: Eb, Vdc	Test conditions: Ec1, Vdc	Test conditions: Ib, mAdc	Test conditions: gm, µmho	Test conditions: Mu	Ib, mAdc Min.	Ib, mAdc Max.	gm, µmho Min.	gm, µmho Max.	Mu Min.	Mu Max.	rp, ohms Min.	rp, ohms Max.	Ic, µAdc max.	Leakage, Ihk, µAdc max.	Emission test: Eb = Ec, Vdc	Emission test: Is, mAdc min.	Cathode type	Base	Bulb	Notes
1	275A	5.0	1.20	330	17	xx	200	−45	47	2800	2.8	30	65	2100	3500	2.4	3.2	800	1300	− 5.0	xx	..	...	O	4	ST-16	
2	45	2.5	1.50	275	..	xx	250	−50	32	2100	3.5	21	40	1750	2450	3.2	3.8	....	....	− 2.0	xx	30	50	O	4	ST-14	
3	6B4G	6.3	1.00	360	15	xx	250	−45	60	5250	4.2	42	82	4050	6750	3.8	4.5	....	....	− 5.0	xx	30	140	O	Oct	ST-16	
	6A3																								4	ST-16	
	2A3	2.5	2.50																			20	90				
	6A5G	6.3	1.25																			30	140	H	Oct	ST-16	(1)
4	1626	12.6	0.25	250	5	100	250	−32	25	2100	5.3	16	34	1600	2600	4.8	5.8	....	....	− 2.0	30	30	70	H	Oct	ST-12	(2)
5	843	2.5	2.50	425	12	...	425	−35	25	1600	8.0	18	32	1350	1900	...	....	3850	5750	− 5.0	100	70	160	H	5	ST-16	
6	271A	5.0	2.00	500	....	100	400	−28	45	3200	8.5	35	55	2600	3900	7.8	9.4	....	....	−10.0	100	..	...	H	5	S-19	(3)
7	2C48	6.3	0.60	550	7.7	100	300	−24	25	3500	9.5	15	35	2500	4600	8.3	10.7	....	....	− 3.0	20	30	65	H	Loc	T-9	(4)
8	6AS7G	6.3	2.50	275	14	330	135		125	7500	2.1	100	150	6300	8700	1.5	2.7	....	....	−4.0	50	10	75	H	Oct	ST-16	(5)
	Developmental type																										
9	SD838	25.0	0.135	...	....	...	250	−32	22	2000	5.5	...	...	....	....	...	....	....	....	......	...	..	...	H	Loc	T-9	(2)

NOTES: Leakage test made at Ehk = 100 Vdc.
(1) Has heater-type cathode, but cathode sleeve is connected internally to heater center tap.
(2) Designed as r-f oscillator and not particularly suited to other applications.
(3) Rated maximum Ik = 65 mAdc.
(4) For cutoff test, Eb = 550 Vdc, Ec1 = − 60 Vdc, Ib = 1.20 mAdc max.
(5) Twin triode with separate cathodes, developmental number A4475. Rated maximum Ik = 125 mAdc per section. Tabular values of Pp, Ib, gm, and Is are per section. Maximum Ic test is for both sections with 1-megohm grid resistor. For cutoff test Eb = 250 Vdc, Ec1 = −200 Vdc, Ib = 10 µAdc maximum. For test conditions no separate bias is used, but cathode resistor of 250 ohms is used in each cathode lead.

14·3. Triodes.—The triodes of this section are divided into classes according to amplification factor, the divisions between classes being at amplification factors of 10 and 25. This division is not entirely arbitrary since, as will be explained, tubes of low, of medium, and of high amplification factors also differ in their other characteristics and in their applications. The tables of the section include not only ordinary triodes but also diode triodes, twin triodes, and triode-connected tetrodes and pentodes.

Low-Mu Triodes.—Low-Mu triodes may be défined as triodes whose amplification factors are less than about 10. Tubes of this classification were formerly widely used as audio power output tubes, and therefore have the general characteristics of comparatively high rated plate dissipation and plate current, and low plate resistance. Triodes have largely

TABLE 10*a*
Interelectrode capacitances

Tube Type	Cgk, $\mu\mu$f			Cpk, $\mu\mu$f			Cgp, $\mu\mu$f		
	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.
45	...	4.0	...	...	3.0	...	...	7.0	...
6B4G, 6A3, 6A5G	...	7.0	...	...	5.0	...	...	16.0	...
2A3	...	7.5	...	...	5.5	...	...	16.5	...
1626	2.3	...	3.6	1.6	...	4.3	3.6	...	4.8
843	3.3	...	4.7	2.0	...	4.0	3.4	...	4.5
271A	5.2	...	7.8	3.0	...	4.6	3.7	...	6.9

been superseded as output tubes by pentodes and beam tetrodes because of their greater efficiency and sensitivity; the higher distortion incurred in their use may be overcome by the use of negative feedback. Low-Mu triodes are now used mainly for special applications for which a high-current triode is desired, as for the series tube in a voltage-regulator circuit.

The characteristics of the low-Mu triodes are shown in Table 10. These are all single triodes except the 6AS7G, which is a twin. Characteristics of low-Mu triode-connected pentodes and beam tetrodes are shown in Table 11.

One of the most desirable characteristics of a tube for use as a series voltage regulator is a low plate-to-cathode voltage drop at zero grid voltage, since this value determines the average tube drop necessary for a particular range of regulation. Tubes whose characteristics best meet

TABLE 11.—TRIODE-CONNECTED TETRODES AND PENTODES (LOW-MU)

Group	Type	Ef, V	If, A	Max. ratings Eb, Vdc	Max. ratings Pp, W	Test conditions Eb, Vdc	Test conditions Ec1, Vdc	Test conditions Ib, mAdc	Test conditions gm, μmhos	Test conditions Mu	Base	Bulb	Notes
1	26A7GT	26.5	0.60	55	2.2	26.5	−5	17.5	5500	3.2	Oct	T-9	(1)
2	89	6.3	0.40	275	.....	250	−31	32	1800	4.7	6, TC	ST-12	(2)
	89Y												
3	6Y6G	6.3	1.25	150	14	150	−17	60	6300	5.4	Oct	ST-14	
	25C6G	25.0	0.30										
4	46	2.5	1.75	275	.....	250	−31.5	22	2350	5.6	5	ST-16	(2)
5	59	2.5	2.00	275	.....	250	−28	26	2600	6.0	7L	ST-16	
6	6K6GT/G	6.3	0.40	315	9.4	250	−23	26	2200	6.4	Oct	T-9	
	7B5										Loc	T-9	
7	25L6	25.0	0.30	125	11.0	120	−10	41	6600	6.4	Oct	Metal	
	25L6G										Oct	ST-12	
	25L6GT/G										Oct	T-9	
	50L6GT	50	0.15								Oct	T-9	
	1632	12.6	0.60		6.0						Oct	Metal	
8	6F6	6.3	0.70	315	12.0	250	−20	31	2600	6.8	Oct	Metal	
	6F6G										Oct	ST-14	
	6F6GT										Oct	T-9	
	42										6	ST-14	
	2A5	2.5	1.75								6	ST-14	
	1621	6.3	0.70		9.0						Oct	Metal	
	6AD7G	6.3	0.85		9.5						Oct	ST-14	(3)
9	35L6GT/G	35.0	0.15	125	9.3	120	−10	40	6000	7.0	Oct	T-9	
	35A5										Loc	T-9	
10	6L6	6.3	0.90	300	21.0	250	−20	40	4700	8.0	Oct	Metal	(4)
	6L6G										Oct	ST-16	
	6L6GA										Oct	ST-14	
	1622			275	15.0						Oct	Metal	
	1631	12.6	0.45	300	17.5						Oct	Metal	
11	12A6	12.6	0.15	275	8.25	250	−17	23	2700	8.9	Oct	Metal	
	12A6GT										Oct	T-9	
12	6V6	6.3	0.45	310	13.2	250	−16	37	4100	9.3	Oct	Metal	
	6V6G										Oct	ST-14	
	6V6GT/G										Oct	T-9	
	7C5										Loc	T-9	
	14C5	12.6	0.225								Loc	T-9	
13	6G6G	6.3	0.15	330	3.0	180	−12	11	2000	9.5	Oct	ST-12	
	6AK6			275							Min	T-5½	
14	6AG7	6.3	0.65	330	8.0	250	−8.5	28	9500	21.0	Oct	Metal	(5)
	6AK7/6AG7												

NOTES: For other characteristics of these types see Tables 21 and 22.
(1) Twin tube; characteristics are for each half.
(2) JAN specification covers triode operation of this type.
(3) Also has small medium-mu triode section.
(4) RCA gives triode-connected Pp rating of 10 W maximum on these types. There appears to be no justification for such a low rating since neither the individual Pp or Pg2 ratings will be exceeded when Pp (total) = 21 W.
(5) This type is included here in spite of the value of Mu since its other characteristics are similar to those of the other types in this table.

this requirement have low Mu and high transconductance. The tube best suited to this application, and which was specifically designed for it, is the 6AS7G (10-8), shown in Fig. 14·9. The two sections in parallel have a plate-current rating of 250 ma. This tube also has a 330-volt heater-to-cathode voltage rating which permits the heater to be operated at ground potential in many cases, thus eliminating the necessity for an additional filament winding on the power transformer. Two other groups of tubes suitable for this application are 10-3 and 11-3. The 6B4G and the others of Group 10-3 have the advantages of higher plate dissipation and maximum plate voltage, and the disadvantages of slightly higher voltage drop and filamentary cathodes. The 6Y6G and others of group 11-3 have slightly lower minimum drop, smaller bulb size, and a 300-volt heater-to-cathode voltage rating. The 6V6GT and others in Group 11-12 are also useful for somewhat lower currents; they have small bulbs and require fairly low heater power.

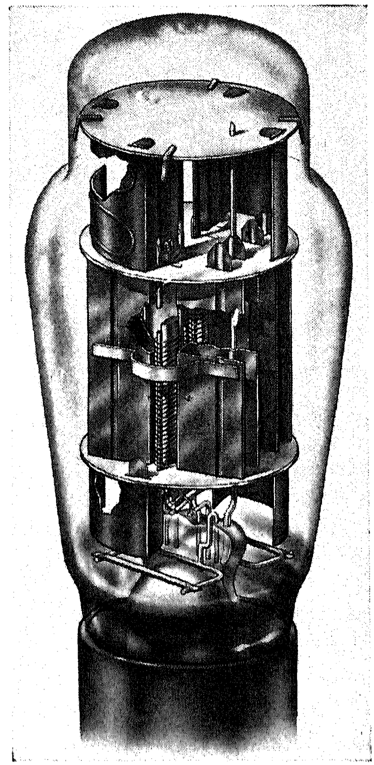


FIG. 14·9.—Twin low-Mu triode 6AS7G.

The 1626, 843, 271A, 2C38, and SD838 are most commonly used as r-f power amplifiers or oscillators. The 6AG7 is listed in Table 11 in spite of its high Mu because its other characteristics when triode-connected are similar to those of the other tubes of Tables 10 and 11.

Medium-Mu Triodes.—For the purposes of classification medium-Mu triodes are considered to be those with amplification factors between 10 and 25. This is, with some exceptions, a satisfactory functional classification also, since lower-Mu tubes are primarily intended as power output tubes and those with higher Mu's are usually employed strictly as voltage amplifiers in lower-frequency circuits. Medium-Mu triodes have the most diversified applications of any class of tubes in these tables. They are used in radar equipment as voltage amplifiers, switch tubes, clamping tubes, sawtooth generators, cathode followers, etc. For many of these applications twin triodes are used since in equipment using a number of such tubes the number of envelopes is approximately halved.

TABLE 12.—MEDIUM-MU TRIODES

Group	Type	Ef, V	If, A	Max. ratings			Test conditions					Cutoff char.		Limits of essential characteristics								Ic μAdc max.	Leak-age, Ihk, μAdc max.	Emis-sion test, Is mAdc min.	Base	Bulb	Notes
				Eb, Vdc	Pp, W	Ehk, Vdc	Eb, Vdc	Ec1, Vdc	Ib, mAdc	gm, μmhos	Mu	Ec1, Vdc	Ib, μAdc max	Ib, mAdc Min.	Ib, mAdc Max.	gm, μmhos Min.	gm, μmhos Max.	Mu Min.	Mu Max.	rp, kilohms Min.	rp, kilohms Max.						
1	352A	10.0	0.32	200	....	100	135	− 6 0	2.4	675	13.1	....	...	1.6	3.2	540	810	12.0	14.3	16	24	−1.0	20	...	6, TC	ST-12	(1)
	6P5GT/G	6.3	0.30									....	...												Oct	T-9	
2	76			275	1.60	100	250	−13.5	5.0	1450	13.8	−15	8	3.7	6.8	1250	1650	....	....	8	11.25	−1.0	20	45	5	ST-12	(2)
	56	2.5	1.00																						5	ST-12	
3	262B	10.0	0.32	200	....	30	135	− 4.5	2.9	950	15.5	....	...	1.8	4.0	750	1150	14.0	17.0	13.5	21	−0.5	5	...	4, TC	ST-12	
	6SR7				2.75																				Oct	Metal	(1)
	6SR7GT																								Oct	T-9	(1)
	6R7	6.3	0.30		2.50																			30	Oct, TC	Metal	(1)
	6R7G				2.75																				Oct, TC	ST-12	(1)
	6R7GT/G				2.50																				Oct, TC	T-9	(1)
4	7E6			275		100	250	− 9.0	9.5	1900	16.0	....	...	6.3	12.7	1500	2300	14.0	13.0	....	....	−1.0	20	55	Loc	T-9	(1)
	6ST7	6.3	0.15																					25	Oct	Metal	(1)
	12SR7																								Oct	Metal	(1)
	12SR7GT				2.75																			30	Oct	T-9	(1)
	12SW7	12.6	0.15																						Oct	Metal	(1), (4)
	14E6																							55	Loc	T-9	(1)
5	2C26A	6.3	1.10	2500	10.0	100	400	−15.0	16.0	2200	16.2	−35	100	10	22	1700	2700	15.0	17.5	....	....	−1.0	100	125	Oct, 2TC	T-9	(2)
6	6L5G	6.3	0.15	275	....	100	250	− 9.0	8.0	1900	17.0	−20	30	5.4	10.6	1500	2300	15.5	19.0	....	....	−1.0	20	30	5	ST-12	
7	6C4	6.3	0.15	330	3.80	100	250	− 8.5	10.5	2200	17.0	−30	50	6.5	14.5	1750	2650	15.5	18.5	....	....	−1.5	20	70	Min	T-5½	
8	6F4	6.3	0.225	165	2.00	90	80	nn	13.0	5800	17.0	−15	300	8.0	18.0	4000	8000	12.0	22.0	....	....	−2.0	20	40	Ac	Ac	(10)

	6C5																								Oct	Metal	
9	6C5G	6.3	0.30	330	2.00	100	250	− 8.0	8.0	2000	20.0	−20	30	5.0	11.0	1700	2500	18.0	22.0	....	....	−1.0	20	40	Oct	ST-12	
	6C5GT/G																								Oct	T-9	
10	HY-615	6.3	0.175	300	3.50	100	250	− 6.0	11.0	2200	20.0	−22	50	8.5	13.5	1760	2640	18.0	22.0	....	....	−1.0	20	75	Oct. 2TC	T-9	
	E1148											−25	100										25				
	6J5																								Oct	Metal	
	6J5GT/G	6.3	0.30																						Oct	T-9	
11	7A4			330	2.75	100	250	− 8.0	9.0	2600	20.0	−24	20	5.5	12.5	2075	3125	18.0	23.0	....	....	−1.5	20	40	Loc	T-9	
	12J5GT	12.6	0.15																						Oct	T-9	
	14A4																								Loc	T-9	
12	2C22	6.3	0.30	330	3.60	100	300	−10.5	11.0	3000	20.0	−26	30	8.5	14.5	2400	3600	....	....	5.2	9.0	−1.5	20	100	Oct. 2TC	T-9	
	7193			500												2700	3300	....	....	5.6	8.0				Oct. 2TC	T-9	(3)
	9002																					−1.0			Min	T-5½	(5)
13	955	6.3	0.15	275	1.80	90	250	− 7.0	6.3	2200	25.0	−50	50	3.6	8.6	1700	2800	....	....	8.4	14.8		20	20	Ac	Ac	(5)
	REL36																					−1.5			Ac	Ac	(5),(6)
14	383A	6.3	0.15	200	1.60	100	120	− 3.0	5.2	2600	25.0	....	...	2.5	8.0	....	....	21.0	29.0	6.0	13.0	−0.1	20	...	Oct	Spec	
													Developmental types														
15	A4442	6.3	0.30	250	.....	...	250	− 9.0	9.5	1900	16.0	....	...	...	....	....	....	....	....	....	....	.....	...	...	Min	T-5½	(1)
16	A4452	12.6	0.15	....	.....	...	...	......	....	.....	....	....	...	....	....	....	....	....	....	....	....	.....	...	...	Min	T-5½	(1),(7)
17	26C6	26.5	0.07	....	....	...	......	....	.....	....	....	....	...	....	....	....	....	....	....	....	....	.....	...	...	Min	T-5½	(1),(8)
18	6K4	6.3	0.15	330	2.25	300	200	− 8.0	8.0	2600	20.0	−30	20	5.0	11.0	2075	3125	18.0	23.0	....	....	−1.0	20	40	SM	T-3	(9)
												−60	2														

Notes: Obsolescent types 27, 37, 55, 85, 6V7G, and 272A are omitted from this table.
(1) Has two diode plates, cathode common with triode section.
(2) Eb = 110 Vdc for cutoff test.
(3) For 20 per cent duty ratio Eb = 500 Vdc.
(4) 12SW7 is 12SR7 selected for operation at Eb = 28 Vdc.
(5) For cutoff test Eb = 150 Vdc and Ecl = −50 Vdc.
(6) Canadian type; has three grid leads.
(7) Characteristics similar to A4442, Group 15.
(8) Designed for operation at Eb = 28 Vdc.
(9) Developmental number SD-834. Same characteristics as 6J5 group or one half of 6SN7. See Table 8b for interelectrode capacitances.
(10) Under "Test conditions," for Ec1, bias is obtained from cathode resistor of 150 ohms.

Other triodes in the medium-Mu class are designed especially for operation at very high frequencies, such as the acorn triodes. Duo-diode triodes are also included since the triode sections of these tubes have essentially the same characteristics as other tubes of the class which lack the diode sections.

Medium-Mu triodes and diode-triodes are listed in order of increasing Mu in Table 12, twin medium-Mu triodes in Table 13, and triode-connected pentodes in Table 14.

TABLE 12*a*
Interelectrode capacitances (medium-mu triodes)
All capacitances are given in $\mu\mu$f

Type	Cgk		Cpk		Cgp		Type	Cgk		Cpk		Cgp	
	Min.	Max.	Min.	Max.	Min.	Max.		Min.	Max.	Min.	Max.	Min.	Max.
352A	1.0	2.0	2.7	4.5	1.0	2.0	6C5	2.4	3.6	7.7	14.3	1.7	2.3
76, 56	2.6	3.8	1.4	2.9	2.6	3.8	6C5G	2.9	4.7	8.4	15.6	1.4	2.6
262B	1.6	3.0	3.0	6.0	1.3	2.5	6C5GT	2.9	4.7	8.4	15.6	1.4	2.6
6SR7	2.4	3.6	2.4	3.4	1.6	3.0	HY-615, E1148	1.1	1.7	0.9	1.5	1.45	1.95
6SR7GT	2.8	4.2	2.8	4.8	1.6	3.0							
6R7	3.5	6.0	3.5	5.0	1.6	3.0							
6R7G	1.5	3.5	3.0	6.5	1.1	4.0	6J5	3.4 Avg		3.6 Avg		3.4 Avg	
6R7GT/G	2.1	3.1	3.6	6.8	1.6	2.8	6J5GT/G	4.2		5.0		3.8	
							7A4	3.4		3.0		4.0	
6ST7	2.8 Avg		3.0 Avg		1.5 Avg		12J5GT	4.2		5.0		3.8	
							14A4	3.4		3.0		4.0	
12SR7	2.4	3.6	2.4	3.4	1.6	3.0							
12SR7GT	2.8	4.2	2.8	4.8	1.6	3.0	2C22, 7193	1.8	2.6	0.3	1.0	3.2	4.0
12SW7	2.4	3.6	2.4	3.4	1.6	3.0	9002	0.95	1.8	0.75	1.45	1.1	1.6
6L5G	3.0 Avg		5.0 Avg		2.7 Avg		955, REL36	0.70	1.3	0.3	0.9	1.0	1.8
6C4	1.8 Avg		1.3 Avg		1.6 Avg		383A	1.0	1.6	0.5	1.1	1.0	1.6

	Cin		Cout		Cgp	
	Min.	Max.	Min.	Max.	Min.	Max.
6P5GT	3.0	4.2	4.4	6.6	2.2	3.0
7E6	2.4	3.6	1.8	4.0	1.0	2.0
14E6	2.4	3.6	1.8	4.0	1.0	2.0
2C26A	2.2	3.0	0.6	1.6	2.3	3.2
6F4	1.4	2.6	0.3	0.9	1.5	2.3

The types in Groups 2, 6, 7, 9, 11, and 18 of Table 12 and in Groups 3, 4, and 5 of Table 13 are so-called "general-purpose" triodes, and therefore find a wide variety of applications. Of these the types in Group

TABLE 13.—MEDIUM-MU TWIN TRIODES

Group	Type	Ef, V	If, A	Max. ratings: Eb, Vdc	Max. ratings: Pp/p, W	Max. ratings: Ehk, V	Test conditions: Eb, Vdc	Test conditions: Ec1, Vdc	Test conditions: Ib/p, mAdc	Test conditions: gm/section, μmhos	Test conditions: Mu	Cutoff char.: Ec1, Vdc	Cutoff char.: Ib/p, μAdc max.	Ib/p, mAdc Min.	Ib/p, mAdc Max.	gm/section, μmhos Min.	gm/section, μmhos Max.	Mu Min.	Mu Max.	rp/section, kilohms Min.	rp/section, kilohms Max.	Ic, μAdc max.	Leakage, Ihk/k, μAdc max.	Emission test, Is/section mAdc min.	Base	Bulb	Notes
1	2C21	6.3	0.60	275	2.3	100	250	−16.5	8.3	1375	10.4	....	..	6.6	10.0	1100	1650	....	....	6.11	9.17	−1.0	20	50	7S, TC	ST-12	(1)
2	2C34	6.3	0.30	330	5.0	100	300	−16	12.5	2150	13.0	....	..	9.4	15.6	1700	2600	11.9	14.1	....	....	−2.0	30	125	7S, 2TC	ST-14	(2), (3)
3	6AH7GT	6.3	0.30	200	1.5	100	180	− 6.5	7.5	1900	16.0	−16	30	5.0	10.0	1500	2300	14	18	....	....	−1.0	20	40	Oct	T-9	(1), (4)
	12AH7GT	12.6	0.15																								
4	7AF7	6.3	0.30	330	2.75	100	250	−10	9.0	2100	16.0	−26	30	5.5	12.5	1700	2500	14	18	....	....	−2.5	20	50	Loc	T-9	(2)
	14AF7	12.6	0.15																								
5	6SN7GT	6.3	0.60	330	2.75	100	250	− 8	9.0	2600	20.0	−24	5	5.5	12.5	2075	3125	18	23	....	....	−2.0	20	40	Oct	T-9	(2), (5), (7)
	6SN7W					250																			Oct	T-9	(2), (5), (7), (8)
	7N7					100						−24	20	6.2	12.6							−1.5		65	Loc	T-9	(1)
	6F8G			275										5.5	12.5									40	Oct, TC	ST-12	(1)
	12SN7GT	12.6	0.30	330																		−2.0			Oct	T-9	(2), (7)
	12SX7GT																								Oct	T-9	(2), (6), (7)
	14N7													6.2	12.6							−1.5		65	Loc	T-9	(1), (6), (7)
	1633	25.0	0.15							....		−25	25	5.5	12.5	1950	3250	....	....			−2.0		40	Oct	T-9	(2), (7)

Developmental type

Group	Type	Ef, V	If, A	Eb, Vdc	Pp/p, W	Ehk, V	Eb, Vdc	Ec1, Vdc	Ib/p, mAdc	gm/section, μmhos	Mu
6	SD705	12.6	0.30	...	7.50	...	250	−15	10.0	2300	12.0

NOTES: Leakage tests are made with Ehk = 100 Vdc and emission tests with Eb = Ec = 30 Vdc except as noted.
(1) Maximum Ic is for each section, tested separately.
(2) Maximum Ic is for both sections connected in parallel.
(3) Has common cathode for both sections. Eb = Ec = 50 Vdc for emission test.
(4) Leakage test is for both sections connected in parallel. For cutoff test Rp = 1 megohm.
(5) For cutoff test Ib may be 5 to 20 μAdc if gm < 0.5 μmho.
(6) Also has specifications for operation at Eb = 28 Vdc.
(7) Maximum Ik/k = 20 mAdc.
(8) For leakage test Ehk = 250 Vdc.
For interelectrode capacitances see Table 13*a*.

12-11, as typified by the 6J5, and the miniature 6C4 (12-7) and the subminiature 6K4 (12-18) are of the latest design of the class, while many of the others are somewhat older. The twin tubes of Groups 13-3, 13-4, and 13-5 are all of recent design.

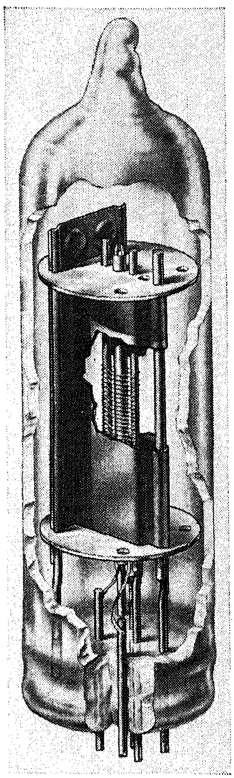


FIG. 14·10.—Subminiature triode 6K4.

The tubes of Groups 8, 10, 13, and 14 of Table 12 are designed primarily for vhf operation, and although they are by no means restricted to such operation it is usually less expensive and more satisfactory to use other types at the lower frequencies. The 6C4 and the tiny 6K4, although well suited to general-purpose applications, will also operate well at high frequencies. The 6K4 is a remarkable little tube. It is essentially a 6J5 or half of a 6SN7 in a subminiature bulb. Its ratings and characteristics are almost the same as those of the larger tubes; it has the added advantage of a 300-volt heater-to-cathode voltage rating; and it will oscillate in suitable circuits up to frequencies as high as 1500 Mc/sec. Only its grid cutoff specifications appear to be inferior. It is shown in Fig. 14·10.

For applications requiring sharp and uniform grid cutoff characteristics, a requirement often encountered in radar equipment, the 6SN7GT or its ruggedized counterpart, the 6SN7W, is unquestionably the best tube in the medium-Mu class. This type has been very extensively used in radar equipment. Except that the 6SN7W has a heater-to-cathode voltage rating of 250 volts, the ruggedized tube should have few advantages over the conventional 6SN7GT in applications not requiring resistance to excessive vibration or shock.

The twin-triode tubes in Groups 13-3 and 13-4 have only half the heater power requirements of the types in Group 13-5, but have somewhat lower Mu's and transconductances.

When considering the comparative merits of twin triodes for a specific application, consideration should also be given to the 6J6 and 7F8, listed under high-Mu triodes in Table 16. Although these types have high Mu's, they also have such high transconductances that their plate resistances are comparable with those of the types in Table 13.

Tubes with more specialized applications in Table 12 are the duo-diode triodes of Groups 1, 4, 15, 16, and 17. These are commonly used as detectors plus audio amplifiers in radio receivers. The 26C6 (12-17) is intended for operation at a plate voltage of 28 volts. The 262B (12-3)

TABLE 13*a*
Interelectrode capacitances (twin medium-mu triodes)

Types	C1g-1k, μμf		C1p-1k, μμf		C1g-1p, μμf		C2g-2k, μμf		C2p-2k, μμf		C2g-2p, μμf		Notes
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	
2C21	2.0	3.2	0.8	2.0	2.0	2.8	1.0	2.2	1.4	2.6	1.4	2.2	
2C34	2.5	4.0	0.3	0.7	1.8	3.0	2.5	4.0	0.3	0.7	1.8	3.0	
6AH7GT, 12AH7GT	2.2	4.2	1.4	3.4	2.0	4.0	1.8	3.8	1.6	3.7	2.0	4.0	(1)
7AF7, 14AF7	1.2	2.0	1.0	2.0	1.6	2.6	1.2	2.0	1.0	2.0	1.6	2.6	(2)
6SN7GT	2.8 Avg		0.8 Avg		3.8 Avg		3.0 Avg		1.2 Avg		4.0 Avg		
7N7, 14N7	3.4		2.0		3.0		2.9		2.4		3.0		(3)
6F8G	3.2		1.0		3.8		1.9		1.9		3.2		
12SN7GT	2.8		0.8		3.8		3.0		1.2		4.0		
1633	3.0		0.8		3.6		2.8		2.2		3.6		

NOTES: (1) C1g-2g = 0.1 μμf max. C1p-2p = 0.8 μμf max.
(2) C1g-2g = 0.20 μμf max. C1p-2p = 0.60 μμf max. C1g-2p = 0.06 μμf max. C2g-1p = 0.10 μμf max.
(3) C1g-2g = 0.40 μμf. C1p-2p = 0.34 μμf. C1g-2p = 0.08 μμf. C2g-1p = 0.06 μμf.

was designed to have minimum hum and noise in low-level audio applications and is still one of the best tubes for the purpose in spite of its low transconductance. Another tube for similar applications is the 1603 pentode, which may be used triode-connected and whose characteristics when so connected are listed in Group 14·2. The 2C26A (12-5) was designed as a pulsed oscillator for operation at about 200 Mc/sec. Its high plate-voltage rating might be of use in other applications. The 2C34 (13-2) is a small twin transmitting triode for vhf applications. It is the only tube in Table 13 that has a common cathode for both sections. This feature is a disadvantage for many applications though not for its original purpose.

High-Mu Triodes.—The characteristics of single high-Mu triodes are given in Table 15, those of twin high-Mu triodes in Table 16, and those of high-Mu triode-connected pentodes in Table 17. In each of these tables the tubes are listed in order of increasing Mu.

In Tables 15 and 16 the tubes may also be considered as divisible into three classes according to their original design purpose. Some types were designed as vhf oscillators and amplifiers; for example, the lighthouse types 2C40 (15-1) and 2C43 (15-3). These tubes will operate up to frequencies as high as 3300 Mc/sec, and although their characteristics are such that they might find application for other purposes their cost and mechanical structure make their use in other than high-frequency applications rather impractical. Other high-frequency tubes are the 7E5/1201 (15-2), which will operate up to 500 Mc/sec, the 6J4 (15-4),

TABLE 14.—TRIODE-CONNECTED PENTODES (MEDIUM MU)

Group	Type	Ef, V	If, A	Maximum ratings		Test conditions					Base	Bulb	Notes
				Eb, Vdc	Pp, W	Eb, Vdc	Ec 1, Vdc	Ib, mAdc	gm, μmhos	Mu			
1	6SJ7	6.3	0.30	275	2.8	250	−8.5	9.2	2500	19	Oct	Metal	(1)
	6SJ7GT										Oct	T-9	
	6SJ7Y										Oct	Metal	
	12SJ7	12.6	0.15								Oct	Metal	
	12SJ7GT										Oct	T-9	
2	6J7	6.3	0.30	275	1.75	250	−8.0	6.5	1900	20	Oct, TC	Metal	(2)
	6J7G										Oct, TC	ST-12	(2)
	6J7GT										Oct, TC	T-9	(2)
	6C6										6, TC	ST-12	(2)
	1603										6, TC	ST-12	(2), (3)
	1620										Oct, TC	Metal	(2), (3)
	12J7GT	12.6	0.15								Oct. TC	T-9	(2)
	57	2.5	1.00								6, TC	ST-12	(2)
3	6AG7	6.3	0.65	330	8.0	250	−8.5	28.0	9500	21	Oct	Metal	

NOTES: (1) Maximum ratings for triode connection are from JAN-1A specifications.
(2) Maximum ratings from RCA specifications.
(3) Special low-noise nonmicrophonic type.
For other characteristics see Tables 19 and 21.

which was designed for operation as a grounded-grid amplifier up to 500 Mc/sec and has extremely high transconductance, and the developmental S491R (15-16), 6N4 (15-19), 2C35 (15-21), and CK603 (15-22). The last two types are subminiatures. Of the twin triodes the 7F8 (16-4) and the 6J6 (16-3) are also suitable for high-frequency operation, and are excellent for more general applications as well, and are commonly so used. In addition to the 6J4, another type which is useful as a grounded-grid amplifier at high frequencies is the 6AK5 when connected as a triode (17-2).

The second class of high-Mu triodes includes those tubes which were originally designed as Class B audio power output tubes and which are listed in Groups 1, 5, 8, and 9 of Table 16. They have been used as Class A amplifiers and in some cases in r-f applications. All have a common

cathode for both sections, however, which is a disadvantage in some circuits, and have been largely superseded by more suitable tubes both for Class A and for r-f applications.

The third class consists of tubes which were originally intended for Class A voltage amplification or for other similar applications having low plate-current requirements. This class includes both twin and single tubes, many of the latter also having two small diode sections. The single types without diodes are those in Groups 15-9, 15-14, and 15-20. The single types with diodes are listed in Table 15, Groups 5, 6, 7, 8, 10, 11, 12, 13, 17, and 18. The twin types are in Groups 16-2, 16-6, and 16-7. All of these types are similar in that the amplification factor ranges from 65 to 100 (except for the 6C8G) and the transconductance under test conditions from 1050 to 1600. Many, however, have some distinctive feature or features that may make one type uniquely fitted for a particular application. Of the single tubes without diodes those in Group 15-14 are to be preferred to those in Group 15-9 since the former have higher amplification factors and transconductances and most are of single-ended construction, while the latter all have top caps. None of these types has found wide application, however, since a diode-triode is usually preferred for receiver use and twin triodes are more popular for other applications. The subminiature SD917 (15-20) has some desirable features including good grid cutoff characteristics and a 300-volt heater-to-cathode voltage rating.

The duo-diode high-Mu triode types have been little used except in radio receivers. The types in Groups 15-5 and 15-6 are of older design since all have top-cap connections. The miniature 6AQ6 (15-7) and 6AT6 (15-8) have desirable characteristics in miniature tubes, while those in Groups 15-11 and 15-12 should be considered if larger tubes are desired. The 6B8G, 75, and 2A5 of the last group are of older design, however, and have top caps and larger bulbs. The 7K7 (15-10) 7X7 (15-13) Z694 (15-17), and Z696 (15-18) are somewhat different from other duo-diode triodes in that one or both of the diode sections have separate cathodes. They are intended for use in discriminator circuits in FM receivers, and should find considerable application for their intended use.

The twin tubes of Table 16 have probably been as extensively used in radar equipment as any class of tubes. Of these the types in Group 16-6 are less often used because they have a common cathode for both sections. The types in Groups 16-3, 16-4, and 16-7 are commonly used. The 6J6 (16-3) has a common cathode, but since it is the only miniature twin triode available it has been very popular. The 7F8 (16-4) has several highly desirable characteristics for use in radar equipment and other devices of a similar nature. It has a 250-volt heater-to-cathode voltage rating, good grid cutoff characteristics, relatively high plate

TABLE 15.—HIGH-MU TRIODES

Group	Type	Ef, V	If, A	Maximum ratings				Test conditions					Limits of essential characteristics						Ic μAdc max.	Leakage, Ihk μAdc max.	Emission test, Is mAdc min.	Base	Bulb	Notes
				Eb, Vdc	Ik, mAdc	Pp, W	Ehk, Vdc	Eb, Vdc	Ec1, Vdc	Ib, mAdc	gm, μmhos	Mu	Ib, mAdc Min.	Ib, mAdc Max.	gm, μmhos Min.	gm, μmhos Max.	Mu Min.	Mu Max.						
1	2C40	6.3	0.75	500	25	5.5	100	250	nn	16.5	4,800	36	....	....	....	.....	..	...	.....	..	..	Oct	LH	(1)
2	7E5/1201	6.3	0.15	275	16	2.75	100	180	−3	5.5	3,000	36	3.0	8.5	2250	3,900	31	41	−1.0	20	30	Loc	T-9	(2)
3	2C43	6.3	0.90	500	40	11.0	100	250	nn	20.0	8,000	48	....	....	....	.....	..	...	.....	..	..	Oct	LH	(3)
4	6J4	6.3	0.40	165	20	2.50	100	150	nn	14.5	12,000	55	9.0	20.0	9000	15,000	40	70	−2.0	20	40	Min	T-5½	(4)
5	6T7G	6.3	0.15	250	..	.....	100	250	−3	1.2	1,050	65	0.6	2.0	800	1,300	50	80	−0.5	20	30	Oct, TC	ST-12	(5)
6	6Q7	6.3	0.30	330	..	.....	100	250	−3	1.0	1,200	70	0.4	2.0	950	1,600	55	85	−0.5	20	30	Oct, TC	Metal	(5)
	6Q7G																					Oct, TC	ST-12	
	6Q7GT																					Oct, TC	T-9	
	12Q7GT	12.6	0.15																			Oct, Tc	T-9	
7	6AQ6	6.3	0.15	330	..	.....	110	250	−3	1.0	1,200	70	0.5	1.8	900	1,600	57	83	−0.6	20	25	Min	T-5½	(5)
8	6AT6	6.3	0.30	330	..	.....	100	250	−3	1.0	1,200	70	....	....	....	.....	..	...	.....	..	..	Min	T-5½	(5)
	12AT6	12.6	0.15																					
9	6K5G	6.3	0.30	330	..	.....	100	250	−3	1.1	1,400	70	0.4	2.0	1100	1,870	55	85	−0.5	20	75	Oct, TC	ST-12	
	6K5GT																					Oct, TC	T-9	
10	7K7	6.3	0.30	330	..	1.1	100	250	−2	2.3	1,600	70	....	....	....	......	..	...	.....	..	..	Loc	T-9	(5), (6)
11	7C6	6.3	0.15	300	..	.....	100	250	−1	1.3	1,000	100	0.7	2.0	750	1,250	85	115	−0.5	20	30	Loc	T-9	(5)
	2A6	2.5	0.80	275									0.45	1.6	825	1,425						6, TC	ST-12	
	6B6G	6.3	0.30																			Oct, TC	ST-12	
	75																					6, TC	ST-12	
	6SQ7																				30	Oct	Metal	

12	6SQ7GT/G			330	..	.....	100	250	−2	0.9	1,100	100	0.5	1.8	825	1,425	85	115	−0.5	20		Oct	T-9	(5)
	12SQ7	12.6	0.15																			Oct	Metal	
	12SQ7GT/G																					Oct	T-9	
	7B6	6.3	0.30	300									0.5	1.4	850	1,470					55	Loc	T-9	
	14B6	12.6	0.15																			Loc	T-9	
13	7X7	6.3	0.30	300	..	.....	100	250	−1	1.9	1,500	100	....	....	....	.....	..	...	.....	..	..	Loc	T-9	(5), (7)
14	7B4	6.3	0.30																			Loc	T-9	
	6F5														1100	2,000						Oct, TC	Metal	
	6F5GT																					Oct, TC	T-9	
	6SF5			330	..	.....	100	250	−2	0.9	1,500	100	0.4	1.7	1100	2,100	85	115	−0.6	20	35	Oct	Metal	
	6SF5GT																					Oct	T-9	
	12F5GT	12.6	0.15												1100	2,000						Oct, TC	T-9	
	12SF5														1100	2,100						Oct	Metal	
	12SF5GT																					Oct	T-9	
	Developmental Types																							
15	M1060	6.3	0.30	nn	20	10.0	...	nn	nn	1.0	500	500	Designed as high-voltage shunt regulator tube.									Oct, TC	T-9	(8)
16	S491R	6.3	0.175	...	..	7.0	...	180	−1	14.0	6,300	58	Designed as oscillator to 400 Mc/sec.									Loc	T-9	
17	Z694	6.3	.....	...	..	.....	...	...	.....	.....	......	...	Similar to 7K7 except for base.									Oct	T-9	
18	Z696	6.3	.....	...	..	.....	..	...	.....	.....	......	...	Similar to 7X7 except for base.									Oct	T-9	
19	6N4	6.3	0.20	...	..	.....	...	...	.....	...	....	...	Characteristics similar to 2C35, short min. bulb.									Min	T-5½	
20	SD917	6.3	0.15	330	..	1.1	300	250	−2	2.3	1,600	70	1.4	3.2	1200	2,000	55	85	−0.2	20	..	SM	T-3	(9)
21	2C35	6.3	0.20	180	..	2.25	..	180	−3.5	12.0	6,000	32	Designed for applications up to 1200 Mc/sec.									SM	T-3	
22	CK603	6.3	0.20	...	..	.....	...	...	.....	.....	......	...	Double-ended triode for uhf applications.									SM	T-3	

NOTE: (1) Designed for applications up to 3370 Mc/sec. Under "test conditions" use 200-ohm bias resistor for Ec1.

(2) Designed for applications up to 500 Mc/sec. Emission test made with Eb = Ec1 = 10 Vdc.

(3) Designed for applications up to 3370 Mc/sec. Under "test conditions" use 100-ohm bias resistor for Ec1. Also has ratings for pulsed operation, eb = 3.5 kv max.

(4) Designed as grounded-grid amplifier up to 500 Mc/sec. Under "test conditions" use 100-ohm bias resistor for Ec1. Cutoff characteristic: Ib = 75 μAdc max at Ec1 = −15 Vdc.

(5) Has two diode plates with following characteristics: I1b = I2b = 1.0 mAdc max. Test conditions: E1b = E2b = 10 Vdc; I1b = I2b = 0.8 mAdc min.

(6) The two diodes have a common cathode which is separate from the triode cathode.

(7) One of the diodes has a separate cathode.

(8) For test conditions adjust Ec1 so that Ib = 1.0 mAdc. Maximum rated value of Eb is 10 kVdc; test value is 5 kVdc.

(9) Cutoff characteristics: Ib = 25 μAdc max when Ec1 = −5.5 Vdc; Ib = 2 μAdc max when Ec1 = −10 Vdc.

Leakage tests made with Ehk = 100 Vdc; Emission tests made with Eb = Ec = 30 Vdc except as noted.

TABLE 15a

Interelectrode capacitances (high-mu triodes)

Type	Cgk, μμf		Cpk, μμf		Cgp, μμf	
	Min.	Max.	Min.	Max.	Min.	Max.
2C40	2.1 Avg		0.02 Avg		1.3 Avg	
7E5/1201	2.8	4.4	2.2	3.4	1.1	1.9
2C43	2.8 Avg		0.02 Avg		1.7 Avg	
6T7G	2.8		3.0		1.5	
6Q7	5.0		3.8		1.4	
6Q7G	3.2		5.0		1.5	
6Q7GT, 12Q7GT	2.2		5.0		1.6	
6K5G	2.0	3.6	4.0	7.5	1.2	2.8
6K5GT	2.0	3.8	3.2	6.2	1.6	4.0
7K7	2.6 Avg		3.0 Avg		1.8 Avg	
7C6	2.4		2.4		1.6	
2A6, 6B6G	1.7		3.8		1.7	
75	1.2	2.2	2.8	4.8	1.2	2.2
6SQ7	3.2 Avg		3.0 Avg		1.6 Avg	
6SQ7GT/G	4.2		3.4		1.8	
12SQ7	3.2		3.0		1.6	
12SQ7GT/G	4.2		3.4		1.8	
7B6, 14B6	3.0		2.4		1.6	
7B4	3.2		3.2		1.6	
6F5	5.0		4.0		2.3	
6F5GT	2.2		3.2		2.8	
6SF5	4.0		3.6		2.4	
12F5GT	2.2		3.2		2.8	
12SF5	4.0		3.6		2.4	
2C35	2.5		0.5		1.5	

NOTES: Capacitance of 2C40 and 2C43 cathode to shell is 100 μμf Av.

For 6J4:
- Cg-(kh) = 4.0 to 6.6 μμf.
- Cp-(kh) = 0.24 μμf max.
- Cgp = 3.3 to 4.5 μμf.
- Chk = 2.5 to 3.9 μμf.

For 6AQ6:
- Cg-(kh) = 1.7 μμf Av.
- Cp-(kh) = 1.5 μμf Av.
- Cgp = 1.8 μμf Av.

For 6AT6 and 12AT6:
- Cg-(kh) = 2.3 μμf Av.
- Cp-(kh) = 1.1 μμf Av.
- Cgp = 2.1 μμf Av.

For 7X7 capacitances are:
- CD1-all = 2.6 μμf Av.
- CD2-all = 2.6 μμf Av.
- CD1-g = 0.1 μμf max.
- CD2-g = 0.1 μμf max.
- CD1-D2 = 0.5 μμf max.

dissipation, high transconductance for a tube of its relatively high Mu, separate cathodes for the two sections, and a small bulb size. In addition the heater power is low for a tube of its capabilities. Its rather unusual construction is shown in Fig. 14·11. The short leads and small electrode size also result in very good high-frequency performance, as mentioned previously.

The 7F8 is of close-spaced construction, and like most tubes using

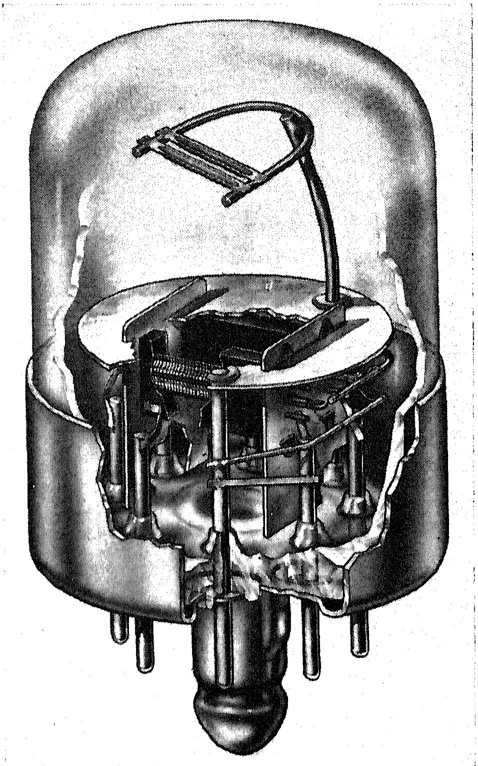


FIG. 14·11.—Twin high-Mu triode 7F8.

close spacing shows somewhat greater variation in characteristics from one sample to another than is the case for tubes with wider spacings. This variation is shown in the diagrams of Fig. 14·12, which shows the spread of transconductance and plate current for a representative group of 7F8's. Each dot indicates the characteristics of one section of one tube. Figure 14·12*a* shows the variations found when the tubes were tested under conditions of fixed grid bias, and Fig. 14·12*b* shows the variations found for the same tubes tested with cathode-resistor bias as specified in Table 16. It will be seen that the spread of values is consider-

TABLE 16.—TWIN HIGH-MU TRIODES

Group	Type	Ef, V	If, A	Maximum ratings		Test conditions					Cutoff char.		Limits of essential characteristics						Ic µAdc max.	Ihk µAdc max.	Emission test		Base	Bulb	Notes
				Eb, Vdc	Pp/p, W	Eb, Vdc	Ec1, Vdc	Ib/p, mAdc	gm/section, µmhos	Mu	Ec1, Vdc	Ib/p, µAdc max.	Ib/p, mAdc		gm/section, µmhos		Mu				Eb = Ec, Vdc	Is/section, mAdc min.			
													Min.	Max.	Min.	Max.	Min.	Max.							
	6N7																						Oct	Metal	
	6N7G																						Oct	ST-14	
1	6N7GT/G	6.3	0.80	330	6.0	300	−6	3.5	1600	35	......	...	2.5	4.5	1360	1850	30	40	−2.0	30	50	125	Oct	T-9	(1), (2), (3), (4)
	6A6																						7L	ST-14	
	53	2.5	2.00																				7L	ST-14	
2	6C8G	6.3	0.30	275	1.0	250	−4.5	3.2	1600	36	−10	25	2.0	4.4	1200	2000	32	40	−1.0	20	30	30	Oct, TC	ST-12	(5), (6)
3	6J6	6.3	0.45	330	1.6	100	nn	8.5	5300	38	−30	75	5.5	12.5	4000	7300	28	48	−2.0	20	10	40	Min	T-5½	(3), (7)
4	7F8	6.3	0.30	330	3.85	250	nn	10.5	5200	50	− 9 −25	700 1	8.0	14.0	4500	6800	40	65	−1.5	10	10	40	Loc	T-9	(5), (6), (8)
5	1635	6.3	0.60	330	3.3	300	−2	1.6	700	65	......	...	2.25	4.35	....	....	..	..	−2.0	20	50	100	Oct	T-9	(3), (4), (9)
	6SC7																						Oct	Metal	(1), (3)
	6SC7GT	6.3	0.30																				Oct	T-9	(1), (3)
6	6SC7GTY			275	....	250	−2	2.0	1325	70	......	...	1.2	2.8	1000	1650	55	85	−1.0	20	30	30	Oct	T-9	(1), (3), (15)
	12SC7	12.6	0.15																				Oct	Metal	(1), (3)
	1634																						Oct	Metal	(1), (3)

	6SL7GT										− 5.5	25	1.4	3.2	1200	2000			−1.0	20	30	40	Oct	T-9	(1), (5)
	6SL7W	6.3	0.30																				Oct	T-9	(1), (5), (11)
7	6SU7GTY			275	1.1	250	−2	2.3	1600	70	.....	.....	1.5	3.1	1275	1925	55	85	.....	10	30	50	Oct	T-9	(5), (12)
	12SL7GT	12.6	0.15																		30	40	Oct	T-9	(1), (5)
	7F7	6.3	0.30								− 5.5	25	1.4	3.2	1200	2000			−1.0	20	30	50	Loc	T-9	(5), (6)
	14F7	12.6	0.15																				Loc	T-9	
	6Y7G																						Oct	ST-12	(3), (4), (6), (13)
8	79	6.3	0.60	275	5.75	250	−2	1.7	700	85	.....	.....	3.7	7.2	....	....	..	..	−1.0	20	30	50	6, TC	ST-12	(1), (3), (4), (13)
9	6Z7G	6.3	0.30	200	4.0	180	0	4.6	....	..	.....	.....	3.2	6.0	....	....	..	..	−1.0	20	30	40	Oct	ST-12	(1), (3), (4)
	Developmental type																								
10	1207 (SD698C)	6.3	0.30	...	....	180	−3.0	5.5	3000	36	......	...	....	....	....	....	..	..	....	..	..	...	Loc	T-9	(14)

Notes: Maximum rated Ehk = 100 V except for 7F8, which is rated 250 V. Leakage test is made at maximum rated Ehk in each case.

(1) Both units tied in parallel for max Ic test.
(2) For Ic test Ec1 = −2Vdc. Maximum rated Ik/k = 70 mAdc.
(3) Common cathode connection for both sections.
(4) Designed primarily for Class B audio amplifier.
(5) Separate connections brought out for the two cathodes.
(6) For Ic test each unit is tested separately.
(7) For the Ic test Eb = 250 Vdc, Rk = 500 ohms, both units are tested in parallel. The characteristics under "test conditions" are for each unit tested separately, but with both units operating. The 6J6 was designed as an r-f amplifier and oscillator to 250 Mc/sec and as a converter to 600 Mc/sec, but is extensively used for other purposes. Under "test conditions," Ec1 is obtained from a cathode resistor of 50 ohms.
(8) The 7F8 is useful at frequencies up to 400 Mc/sec. Under "test conditions," Ec1 is obtained from a cathode resistor of 200 ohms.
(9) For the Ic max test Ec1 = −2Vdc; each unit is tested separately.
(10) The 1634 is a 12SC7 selected for match between sections.
(11) The 6SL7W is a ruggedized 6SL7.
(12) The 6SU7GTY has special tests for Ic and match between sections. It has a low-loss base and is suitable for use as a d-c amplifier.
(13) The limits of Ib are for Ec1 = 0 Vdc.
(14) The 1207 has common plates and common cathodes. It is intended for converter use up to 600 Mc/sec.
(15) Has a low-loss base.

TABLE 16*a*

Interelectrode capacitances (twin high-mu triodes)

Type	C1g-1k, $\mu\mu f$		C1p-1k, $\mu\mu f$		C1g-1p, $\mu\mu f$		C2g-2k, $\mu\mu f$		C2p-2k, $\mu\mu f$		C2g-2p, $\mu\mu f$		Notes
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	
6C8G	2.6 Avg		2.0 Avg		2.6 Avg		1.3 Avg		2.2 Avg		1.8 Avg		(1)
6J6	1.4	2.6	0.25	0.65	1.2	1.8	1.4	2.6	0.25	0.55	1.2	1.8	(2)
7F8	2.1	3.5	1.0	1.8	0.9	1.5	2.1	3.5	1.0	1.8	0.9	1.5	(3), (4)
6SC7	1.2	2.8	2.0	4.0	...	2.4	1.2	2.8	2.0	4.0	...	2.4	(3)
12SC7	1.2	2.8	2.0	4.0	1.6	2.4	1.2	2.8	2.0	4.0	1.6	2.4	(3)
6SL7GT, 12SL7GT	3.0 Avg		3.8 Avg		2.8 Avg		3.4 Avg		3.2 Avg		2.8 Avg		(5)
7F7, 14F7	2.4		2.0		1.6		2.4		2.0		1.6		(3), (6)

NOTES: (1) C1g-2g = 0.1 $\mu\mu f$ Av., C1p-2p = 2.0 $\mu\mu f$ Avg.
(2) Chk = 3.3 $\mu\mu f$ min, 7.5 $\mu\mu f$ max.
(3) Capacitances under "Cg-k" and "Cp-k" are actually Cin and Cout.
(4) C1g-2g = 0.02 $\mu\mu f$ min, 0.06 $\mu\mu f$ max.
C1p-2p = 0.20 $\mu\mu f$ min, 0.50 $\mu\mu f$ max.
Chk = 2.7 $\mu\mu f$ min, 4.5 $\mu\mu f$ max.
(5) C1g-2g = 0.65 $\mu\mu f$ Avg, C1p-2p = 0.4 $\mu\mu f$ Avg, C2g-1p = 0.13 $\mu\mu f$ Avg.
(6) C1g-2g = 0.2 $\mu\mu f$ Avg, C1p-2p = 1.0 $\mu\mu f$ Avg.

ably reduced by the use of resistor bias, and for this reason this type of bias should be used whenever possible. This is generally true of all

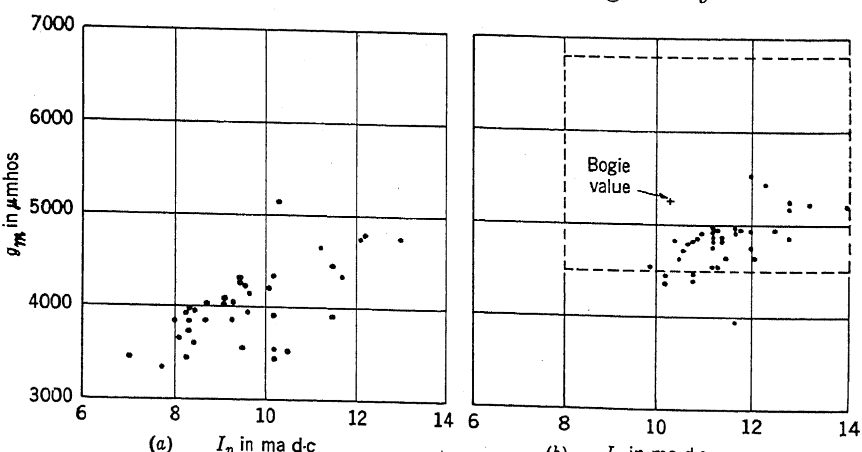


FIG. 14·12.—Variation of plate current and transconductance of 7F8 tubes. (*a*) With fixed bias; (*b*) with resistor bias.

closed-spaced tubes, such as the 6J6 and the pentode types 6AC7, 6AK5, and 6AG5 of Table 18, to mention only a few.

The 6SU7GTY (16-7) is identical in most respects with the more commonly used 6SL7GT but has specifications to ensure a high degree of

TABLE 17.—TRIODE-CONNECTED PENTODES (HIGH-MU)

Group	Type	Ef, V	If, A	Maximum ratings			Test conditions					Cutoff char		Base	Bulb	Notes
				Eb, Vdc	Ik, mAdc	Pp, W	Eb, Vdc	Ec1, Vdc	Ib, mAdc	gm, μmhos	Mu	Ec1, Vdc	Ib, μAdc max			
1	6SH7	6.3	0.30	330	..	2.50	250	−5	8.5	4800	31	−6.5	50	Oct	Metal	(1)
	6SH7GT													Oct	T-9	
	6SH7L													Oct	T-9	
	12SH7	12.6	0.15											Oct	Metal	
	12SH7GT													Oct	T-9	
2	6AK5	6.3	0.175	200	20	1.85	180	−4	8.0	5700	31	.....	..	Min	T-5½	
3	6AC7	6.3	0.45	330	..	2.25	250	−5.5	8.0	6600	35	.....	..	Oct	Metal	
4	6AG5	6.3	0.30	330	..	2.50	250	−4.5	5.5	3800	42	.....	..	Min	T-5½	(2)

NOTES: (1) For cutoff test Eb = 150 Vdc.
(2) RCA ratings for triode operation are identical with those in table.

uniformity between sections and is thus desirable when accurate balance is important. It also has a low-loss base.

The M1060 (15-15) has some unique and interesting features, although at present it is in the developmental stage. It is intended to be used as a shunt regulator tube in high-voltage power supplies for cathode-ray tubes, and accordingly has a much higher voltage rating than any other small receiving tube. It also has the unusually high amplification factor of approximately 500. A typical 8-kv supply using this tube as the regulating element and a 300-volt regulated voltage as the comparison standard showed output variations of approximately 0.6 per cent for changes of output current from 0 to 0.5 ma, and approximately ± 0.3 per cent for input-voltage variations of ± 10 per cent.

The early experimental M1060's that were tested at the Radiation Laboratory were very satisfactory electrically and mechanically but had rather short lives. Most samples showed cathode emission failures after about 100 hr at 8 kv and 1 ma. A few tubes were unstable due to grid current flow through the necessarily high grid resistor. A somewhat higher transconductance would be desirable and a reduction of amplification factor by a factor of 2 could be tolerated in voltage-regulating applications. These changes would result in more stable operation and better regulation.

Another tube that can be used in shunt voltage-regulating circuits is the 15E (not listed in these tables). This is a small transmitting triode that was originally designed as a pulsed oscillator in vhf circuits but which will operate in the same type of circuit that is used for the M1060. It is far less effective, however, since it has a Mu of only 20, and it requires 20 watts of filament heating power.

Table 17 lists the characteristics of a number of high-Mu triode-connected pentodes. It will be noted that all of them have high transconductance when so connected, higher in fact than any of the regular triodes except the 7F8 and 6J6 and some of the specialized high-frequency tubes. Figure 14·13 shows the variation of Mu, transconductance, and plate resistance, with variations of plate current for a triode-connected 6AG5 at two different plate voltages. The high transconductance is of value in applications as a cathode follower, for which a tube with both a high transconductance and a high Mu is required.

As far as the principal uses of the Radiation Laboratory were concerned, the most valuable triodes were the following:

6SL7—Dual unit with separate cathodes, used in high-gain d-c and low-frequency a-c amplifiers in which a plate current of less than 10 ma was sufficient. Sharp cutoff characteristics. Sections well matched, useful as amplitude comparators and selectors, and as differential amplifiers. Very low grid current.

6SU7—Same as 6SL7 except low-loss base and selected for match between sections. 6SU7 matching specifications are passed by about 50 per cent of production 6SL7's.

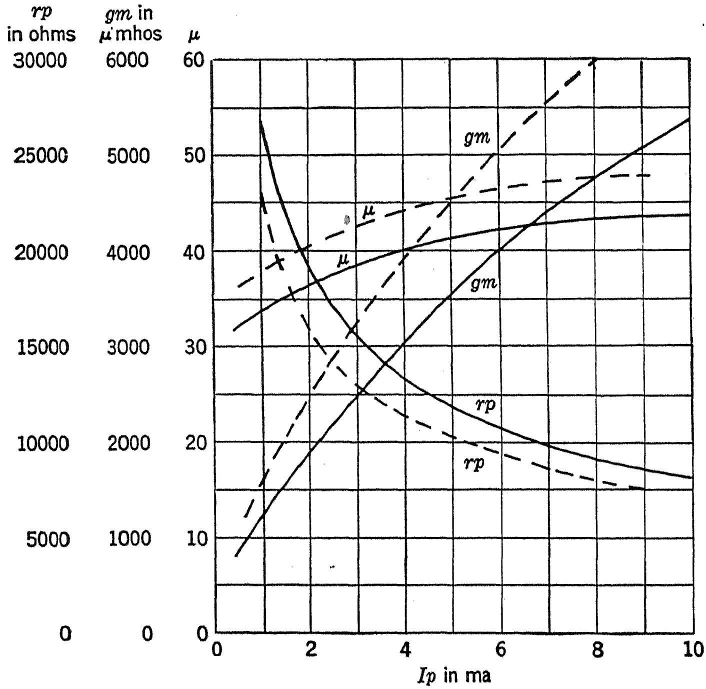


FIG. 14·13.—Plate resistance, transconductance, and Mu of triode-connected 6AG5 as a function of plate current. Solid curves: Eb = 250 Vdc. Dashed curves: Eb = 150 Vdc.

6SN7—Dual medium-Mu unit with separate cathodes. Generally useful in pulse circuits and as oscillator and amplifier for moderate powers. Will stand great abuse. Best small blocking oscillator as power gain is high even with grid at high positive voltage. Often used as double diode before advent of 6AL5 (far better than 6H6). When used as switch tube in sweep circuits gives most uniform clamping. In pulse circuits it is useful as an amplifier up to 2 or 3 Mc/sec, above which the effects of Cgp are excessive. Grid cutoff not very sharp. Most used as blocking oscillator, multivibrator, etc. Very large grid resistor may be used without serious effects even at maximum plate dissipation.

6J6—Miniature dual unit with common cathode. Designed as uhf oscillator. Large transconductance, low capacitance, medium Mu, matching between sections poor. Cutoff not very sharp. Tendency for grid to limit and block if large grid resistor is used. Not a very good sweep clamp. An excellent diode. Better video

amplifier than 6SN7 because of higher Mu and lower capacitance. (Plate resistance is about the same.)

6C4—Miniature single unit approximately equivalent to half of a 6SN7. Somewhat lower capacitances.

6K4—Subminiature single unit. Same specifications as 6SN7, low heater power, lower capacitances, very ruggedly constructed.

6B4—(Also 2A3, 6A3, etc.) High current, low Mu, low plate resistance, filamentary triode, most used as regulator tube in series-type voltage regulators. Low-distortion audio amplifier.

6AS7—Dual high-current heater-type triode for voltage regulators; one tube will regulate two separate 100-ma supplies.

3A5—(Not listed in tables.) Best filamentary triode for pulse use. Blocking oscillator, multivibrator, etc.

14·4. Tetrodes and Pentodes.—Tetrodes and pentodes are most conveniently classified according to function rather than to structure, and the tubes of this section will be classified primarily as r-f amplifiers or as power output tubes. There are many tubes which might be considered as belonging in either or both of these categories, but the great majority fall clearly into one or the other class.

R-f Amplifiers.—R-f and i-f amplification in radio receivers is now almost invariably obtained from small pentodes, which may be classified on the basis of their cutoff characteristics into sharp-cutoff and remote-cutoff types. The latter type is occasionally and rather meaninglessly designated the "super control" type, and in some tube lists the former type is vaguely called a "triple grid amplifier." Some tubes are intermediate in character between the two classes, and are called "semi-remote-cutoff" pentodes; they may most conveniently be classed with the remote-cutoff tubes.

Sharp-cutoff pentodes have Eg-Ip characteristics such that plate current and transconductance decrease to practically zero when the control grid is made a few volts negative. In a remote-cutoff pentode they will decrease rapidly at first with increasing negative grid bias, but the rate of decrease becomes less and the quantities become essentially zero only when the negative bias becomes comparatively large. This remote-cutoff or variable-Mu characteristic is desirable when a variable bias voltage is used to control the gain of the tube as in the ordinary receiver AVC circuit.

Representative curves of transconductance vs. grid bias voltage are shown in Fig. 14·14. The 6SK7 (curve *a*) and the 6SJ7 (curve *c*) are almost identical tubes except that the former is remote-cutoff and the latter is sharp-cutoff. Likewise the 6SG7 (curve *b*) and the 6SH7 (curve *d*) are almost identical except that the cutoff of the former is semiremote and that of the latter is sharp. Of the two sharp-cutoff

tubes the 6SH7 cuts off at a considerably less negative grid voltage than does the 6SJ7: in fact it has probably the sharpest cutoff of any pentode listed.

Sharp-cutoff pentodes are listed in Table 19 and remote- and semi-remote-cutoff pentodes in Table 20, in order of decreasing transconduc-

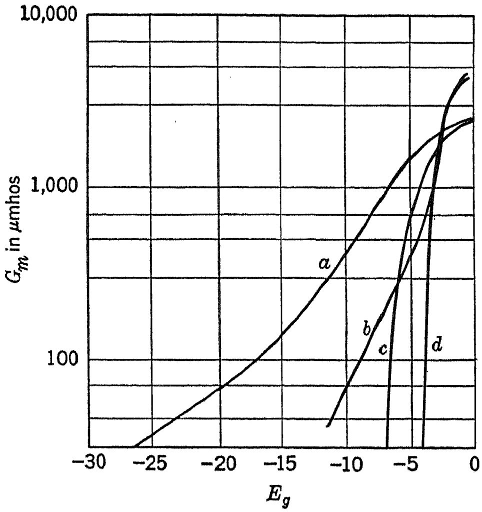


FIG. 14·14.—Cutoff characteristics of typical r-f pentodes. (a) 6SK7, remote cutoff; (b) 6SG7, semiremote cutoff; (c) 6SJ7, sharp cutoff; (d) 6SH7, sharp cutoff.

tance in each case. For many applications it is desirable to have as high a transconductance as possible, but in probably the majority of applications a more important quantity is the figure of merit of the tube, or the ratio of transconductance to interelectrode capacitance. In such applications as video amplifiers or wideband i-f amplifiers the gain for a given bandwidth will be exactly proportional to the figure of merit in such circuits as a shunt-peaked video amplifier, and approximately proportional in other circuits. Table 18 lists the figures of merit of many of the tubes of Table 19 and some from Table 20.

Types marked * in Table 18 are acorn, miniature, or subminiature construction. Those marked ** are of some special construction, such as the 713A and 717A precursors of the 6AK5, which had similar electrode structures and very small bulbs but standard bases. It will be noted that most of the types with figures of merit over 400 are of miniature, subminiature, acorn, or special construction. The only "standard-sized" tubes with high figures of merit are the 6AC7 and 6AC7W and the British types VR91, VR91A, and EF50. It may also be noted that most of the tubes in the table with figures of merit over 300 are of the sharp-cutoff type, a few are semiremote-cutoff, and none is remote-cutoff. The

TABLE 18.—FIGURES OF MERIT OF R-F AMPLIFIERS

Type	Figure of merit	Cutoff
A4444C*	920	SR
6AK5*	745	S
6AG5*	600	S
CK604A*	580	S
713A**	575	S
6AC7, 6AC7W	560	S
6AS6*	500	S
384A**	500	S
6AU6*, A4464*	495	S
717A**	495	S
VR91, VR91A, EF50	465	S
385A**	445	S
6BA6*, 12BA6*	440	SR
6AJ5*	435	S
7V7	390	S
6AB7	385	SR
7W7, 14W7	350	S
6SH7, 6SH7GT, 12SH7, 12SH7GT	315	S
1205	315	S
7R7, 14R7	310	SR
6SG7, 6SG7GT, 12SG7GT	305	SR
956*	280	R
9003*	280	R
954*	220	S
9001*	210	S
6SK7, 12SK7, 7A7, 14A7	155	R
6SJ7, 6SJ7Y, 12SJ7	125	S

last two groups in the table, as represented by the 6SK7 and 6SJ7, are typical of modern "general purpose" remote-cutoff and sharp-cutoff pentodes in which a high figure of merit was not one of the design objectives.

A high figure of merit should not be taken as an indication of the value of a given type for all applications, however, since other desirable characteristics may be sacrificed to obtain this figure. The types with a high figure of merit are usually of close-spaced construction and therefore frequently show greater variation in characteristics than more conventional types. It may be noted from Table 19 that many of the types with high transconductances are tested with resistor bias. Under these conditions the deviations from the normal or "bogie" values of essential characteristics for a representative group of tubes will be only about

half as great as if the test were made with fixed bias. This effect was illustrated for the 7F8 triode in Fig. 14·12. For audio-frequency applications, especially at low power levels, tubes with high transconductances may not be desirable. One manufacturer states that the 6AC7 and 6SH7 are generally unsuitable for such uses because trouble may be encountered from heater hum unless a d-c heater supply is used.

The tubes listed in Group 19-1 have the highest transconductance of any pentodes of similar size. For this reason they have been extensively used in radar equipment as video and i-f amplifiers, as multivibrators when a fast rise and fall are desired, and for various other applications. Their figure of merit, while higher than those of any other standard-sized tubes, is less than those of some of the newer miniature and subminiature tubes. The 1851 is the parent of the other tubes of the group and may be considered obsolescent.

Group 19-2 includes three similar British tubes, which are included because they have some interesting features and because they were used in some equipment intended for joint British-American use during the war. At least two of them, the EF50 and the VR91A, were manufactured in this country. They have values of transconductance exceeded only by the tubes of the previous group and by the developmental types A4481A (19-27) and A4485 (19-28) and by two of the developmental types of Table 20. They have fairly good g3 control characteristics, a feature that will be discussed later in connection with the 6AS6.

The three types in Group 19-3 are roughly the loctal equivalents of the types in Group 19-8. They are also the nearest loctal equivalents to the tubes of Group 19-1, but differ considerably from both groups in construction and characteristics. The 7V7, 7W7, and 14W7 are actually hexodes, but since g2 and g3 are internally connected and function as a single screen grid they are usually considered as pentodes. The 7W7 and 14W7 have two separate cathode pins to permit the isolation of input and output circuits in high-frequency amplifiers. These types also have specifications on the g4 (suppressor grid) cutoff characteristics, as discussed later. The 1231 (19-4) and the 7G7/1232 (19-9) are predecessors of the types in Group 19-3 and may be considered obsolescent.

Groups 5, 6, and 7 of Table 19 list three similar high-transconductance miniature pentodes, the 6AU6, 6AK5, and 6AG5. All have approximately the same transconductance, but the 6AK5 has the highest figure of merit of any high-production type.[1] It is more uniform than most high-transconductance tubes; note that the test conditions specify fixed bias. The input and output capacitance limits are also much tighter than for any comparable type. The maximum grid current is very low,

[1] G. T. Ford, "Characteristics of Vacuum Tubes for Radar Intermediate Frequency Amplifiers," *Bell System Tech. Jour.*, **25**, 385–407 (July 1946).

TABLE 19.—SHARP-CUTOFF PENTODES

Group	Type	Ef, V	If, A	Maximum ratings					Test conditions						Cutoff char.		Limits of essential characteristics						Ic1 μAdc max.	Leakage test, Ihk μAdc max.	Emission test		Base	Bulb	Notes
				Eb, Vdc	Ec2, Vdc	Pp, W	Pg2, W	Ehk, Vdc	Eb, Vdc	Ec2, Vdc	Ec1, Vdc	Ib, mAdc	Ic2, mAdc	gm, μmhos	Ec1, Vdc	Ic1, μAdc max.	Ib, mAdc Min.	Ib, mAdc Max.	Ic2, mAdc Min.	Ic2, mAdc Max.	gm, μmhos Min.	gm, μmhos Max.			Eb, Vdc	Is, mAdc min.			
1	6AC7																				7000	11,000					Oct	Metal	
	6AC7W	6.3	0.45	330	165	3.3	0.45	100	300	150	nn	10	2.5	9000	− 6.0	900	8.0	12.5	1.6	3.4			......	20	10	40	Oct	Metal	(1)
	6AJ7/6AC7																				7000	12,500					Oct	Metal	
	1851																										Oct, TC	Metal	
2	EF50						1.0				nn						8.0	12.5					−1.0						
	VR91	6.3	0.30	300	300	3.0	1.7	140	250	250	−2	10	3.0	6500	......	......	7.5	12.5	2.2	4.0	5200	7,800	−0.5	20	10	65	nn	nn	(2)
	VR91A										nn						8.0	12.5											
3	7V7	6.3	0.45																1.0	6.0									
	7W7			330	165	4.0	0.8	100	300	150	nn	10	3.9	5800	− 8.0	10 Av.	8.0	12.5	0.78	6.25	4650	6,950	−1.0	30	10	70	Loc	T-9	(3), (4)
	14W7	12.6	0.225																										
4	1231	6.3	0.45	330	175	3.3	....	.	300	150	nn	10	2.5	5500	− 9.0	10	8.5	11.5	0.5	5.0	5100	6,200	−1.5	30	20	110	Loc	T-9	(5)
5	6AU6	6.3	0.30	330	165	3.3	0.7	100	250	150	−1	10.8	4.3	5200	− 6.2	10 Av.	.	....	....	....	....	......	......	..	..	...	Min	T-5½	
6	6AK5	6.3	0.175	200	155	1.85	0.55	100	120	120	−2	7.5	2.5	5000	−10.0	200	3.0	12.0	0.8	4.0	3500	6,500	−0.1	30	..	...	Min	T-5½	(3), (6), (7), (8)
7	6AG5	6.3	0.30	330	165	2.5	0.55	100	250	150	nn	7.0	2.0	5000	− 9.0	30	5.2	8.8	1.3	2.7	4000	6,000	−1.0	20	10	25	Min	T-5½	(3), (5), (6), (7)
8	6SH7																										Oct	Metal	
	6SH7GT	6.3	0.30																								Oct	T-9	
	6SH7L			330	165	3.3	0.7	100	250	150	−1	10.8	4.0	4900	− 6.5	50	8.2	13.4	2.0	6.0	3920	5,880	−1.0	20	20	95	Oct	T-9	(3), (6), (7), (9)
	12SH7	12.6	0.15																								Oct	Metal	
	12SH7GT																										Oct	T-9	
9	7G7/1232	6.3	0.45	275	110	1.7	0.3	100	250	100	−2	6.0	2.0	4500	− 7.0	100	4.2	8.4	0.4	3.2	3700	5,600	−1.5	20	20	110	Loc	T-9	
0	713A	6.3	0.175	200	130	....	....	100	120	120	−2	7.5	2.4	3900	−10.0	100	3.0	12.0	0.8	4.0	2700	5,200	−0.1	30	...	...	Oct	Spec	(3), (6)
	717A																												

1	6AS6	6.3	0.175	200	155	1.85	0.85	100	120	120	−2	5.7	3.0	3500	−10.0	100	2.5	9.0	....	6.0	2500	4,500	−0.2	20	..	...	Min	T-5½	(8), (10)
2	VR116 (Br.)	6.3	0.63	250	200	....	....	...	200	200	−4	6.7	...	3350	......	......	...	....	....	....	....	......	......	..	..	...	nn	nn	(11)
3	7L7	6.3	0.30	330	140	1.65	0.33	100	250	100	−1.5	4.5	1.5	3100	− 5.0	100	2.9	6.3	0.3	2.4	2550	3,850	−1.0	20	20	70	Loc	T-9	
4	6AJ5	6.3	0.175	200	155	1.85	0.55	100	28	28	nn	2.9	1.0	2700	− 5.0	50	1.8	4.0	0.1	2.0	2000	3,500	−0.25	20	..	.	Min	T-5½	(3), (6), (8)
5	384A	6.3	0.15	275	130	1.85	0.55	100	120	120	−2	5.0	1.7	2500	−10.0	200	2.0	8.0	..	3.5	1700	3,300	−0.20	20	..	...	None	Spec	
	385A					....																					Oct, TC	Spec	
6	310A	10.0	0.315	275	180	2.5	0.4	150	135	135	−3	5.6	1.5	1875	−12.0	50	3.7	7.5	0.5	2.5	1500	2,250	−0.5	20	..	...	6, TC	ST-12	
	328A	7.5	0.422																										
7	6SJ7	6.3	0.30	330	140	2.8	0.7	100	250	100	−3	3.0	0.8	1650	−10.0	30	2.0	4.0	0.4	1.2	1325	1,975	−0.5	20	30	60	Oct	Metal	
	6SJ7GT																										Oct	T-9	
	6SJ7Y																										Oct	Metal	
	12SJ7	12.6	0.15																								Oct	Metal	
	12SJ7GT																										Oct	T-9	
8	14C7	12.6	0.15	330	110	1.0	0.1	100	250	100	−3	2.2	0.7	1575	− 8.5	30	1.5	3.0	0.1	1.1	1300	1,950	−0.5	20	30	40	Loc	T-9	
9	954	6.3	0.15	275	110	1.0	0.55	90	250	100	−3	2.0	0.7	1400	−10.0	25	1.0	3.0	0.3	1.25	1000	1,800	−1.0	20	15	20	Ac	Ac	(7)
	9001																		0.3	1.1							Min	T-5½	(3), (7)
20	7C7	6.3	0.15	330	110	1.0	0.1	100	250	100	−3	2.0	0.5	1300	−8.5	30	1.4	2.8	0.1	0.8	1050	1,600	−0.5	20	30	60	Loc	T-9	
21	77	6.3	0.30	330	110	0.8	0.11	...	250	100	−3	2.3	0.5	1250	−8.0	30	1.5	3.1	0.3	0.8	1025	1,475	−0.5	20	30	45	6, TC	ST-12	
22	6J7	6.3	0.30	330	140	0.8	0.11	100	250	100	−3	2.0	0.5	1225	− 8.0	30	1.3	2.9	0.2	1.0	1000	1,450	−0.5	20	30	45	Oct, TC	Metal	(1), (21)
	6J7G																										Oct, TC	ST-12	
	6J6GT																										Oct, TC	T-9	
	6C6														− 8.0	25											6, TC	ST-12	
	1620			275	110	....	....	...							......	...	...	....	....	....	....	....					Oct, TC	Metal	
	1603				200																						6, TC	ST-12	
	12J7GT	12.6	0.15	330	140	0.8	0.11	100							− 8.0	30	1.3	2.9	0.2	1.0	1000	1,450					Oct, TC	T-9	
	57	2.5	1.00	275	110										− 7.5	30											6, TC	ST-12	
	6W7G	6.3	0.15	330	110	0.55	0.11								− 8.0	30											Oct, TC	ST-12	

TABLE 19.—SHARP-CUTOFF PENTODES.—(Continued)

Group	Type	Ef, V	If, A	Maximum ratings					Test conditions						Cutoff char.		Limits of essential characteristics						Ic1 μAdc max.	Leakage test, Ihk μAdc max.	Emission test		Base	Bulb	Notes
				Eb, Vdc	Ec2, Vdc	Pp, W	Pg2, W	Ehk, Vdc	Eb, Vdc	Ec2, Vdc	Ec1, Vdc	Ib, mAdc	Ic2, mAdc	gm, μmhos	Ec1, Vdc	Ic1, μAdc max.	Ib, mAdc		Ic2, mAdc		gm, μmhos				Eb, Vdc	Is, mAdc min.			
																	Min.	Max.	Min.	Max.	Min.	Max.							
														Developmental types															
23	SD828A	6.3	0.15	330	165	2.25	0.7	300	200	150	−1	6.7	2.0	2950	−10.0 −20.0	20 2	4.5	9.0	1.2	2.8	2200	3,700	−0.2	20	10	....	SM	T-3	(13)
24	SD828E	Similar to SD828A but has higher gm and grid lead out the top.																									SM	T-3	
25	CK602	6.3	0.20	Similar to 6AK5 and CK604A but has double-ended construction and integral g2 to k bypass condenser.																							SM	......	
26	CK604A	6.3	0.20	200	155	1.85	0.55	100	120	120	−2	7.5	2.5	5000	−12.0	10 Av.	....	.....	....	....	....	......	......	..	..	.	SM	T-4½	(14)
27	A4481A	6.3	0.30	Similar to miniature type A4485; gm = 8500 μmhos.																							Ac	Ac	
28	A4485	6.3	0.30	Similar to acorn type A4481A; gm = 8500 μmhos.																							Min	T-5½	
29	A4464	12.6	0.15	Identical with 6AU6 (Group 5 above) except for heater ratings.																							Min	T-5½	
30	1205 (SD673D)	6.3	0.30	...	...	....	....	...	300	150	nn	6.5	2.0	3100	.....	.....	....	.....	....	....	....	.....	.....	..	...	....	Loc	T-9	(3), (15)

NOTES: For leakage test Ehk = 100 Vdc except for SD828A, for which it is 300 Vdc. For emission test Eb = Ec1 = Ec2 = suppressor grid voltage for all types which have separate suppressor-grid lead: or other types the suppressor voltage is naturally zero with respect to the cathode. All tubes in this table are heater-type. Suppressor grids are brought out to a separate pin except as denoted by Note (6).

(1) Under "test conditions," Ec1 is obtained from 160-ohm cathode resistor. The 6AC7W is a ruggedized 6AC7; the 6AJ7/6AC7 has a ring contact for direct grounding of the shell and has specifications for g3 cutoff; Ec1 = −3 Vdc, Ec3 = −150 Vdc, Ib = 150 μAdc max.

(2) The EF50, VR91, and VR91A are British tubes but the EF50 and VR91A have been manufactured in this country. All three have a glass bulb covered by a metal shell and a British 9-pin locking base. Under "test conditions," Ec1 is obtained from a 150-ohm cathode resistor in the cases of the EF-50 and the VR91A. All three have specifications for g3 cutoff; Ec3 = −60 Vdc, Ib = 0 min, 2.0 μAdc max.

(3) Has two cathode connections for high-frequency applications.

(4) These types have 4 grids, but g2 and g3 are internally connected and function as a screen grid; g4 is the suppressor grid. The 7V7 does not have the second cathode connection. All have specifications for g4 cutoff; Ec4 = −70 Vdc, Ib = 200 μAdc max and (except for the 7V7) gm = 50 μmhos max. Under "test conditions," Ec1 is obtained from 160-ohm cathode resistor.

(5) Under "test conditions," Ec1 is obtained from 200-ohm cathode resistor.

(6) Suppressor grid is internally connected to cathode.

(7) Useful as an amplifier up to approximately 400 Mc/sec.

(8) Maximum rated Ik = 20 mAdc.

(9) The 6SH7L differs from the 6SH7GT only in its Cgp and in being 0.32 in. shorter. For the cutoff test, Eb = Ec2 = 150 Vdc, Ec1 = −6.5 Vdc, "Ib" in table = total Ik. For the Ic1 max test Ec1 = −1.5 Vdc.

(10) Has specifications for g3 cutoff; Ec3 = −15 Vdc, Ib = 20 μAdc max. Also has specifications for g3-p transconductance of 400 to 1400 μmhos for Ec3 = −3 Vdc.

(11) Has a sharp g3 cutoff characteristic; Ec1 = −3 Vdc, Ec3 = −7.5 Vdc, Ib = 200 μAdc Av. British Mazda octal base. This is a British tube and is included in this table because it and the 6AS6 are the only types available with a sharp g3 cutoff.

(12) The 1620 is a nonmicrophonic 6J7, the 1603 is essentially a 6C6 with very low noise and microphonic output; both types are intended primarily for low-level audio-frequency applications.

(13) For leakage test Ehk = 300 Vdc. Has specifications for g3 cutoff; Ec3 = −50 Vdc, Ib = 20 μAdc max. For Ic1 max test Ec1 = −2 Vdc.

(14) This type has an external metallic shielding coating, connected to a separate lead. Maximum rated Ik = 12 mAdc.

(15) For applications at frequencies up to 200 Mc/sec.

TABLE 19a
Interelectrode capacitances (sharp-cutoff pentodes)

Type	Cin, μμf Min.	Cin, μμf Max.	Cout, μμf Min.	Cout, μμf Max.	Cgp, μμf, max.
.C7					
AC7W	8.8	13.2	3.5	6.5	0.015
.J7/6AC7					
351	8.4	12.6	3.7	6.7	0.015
F50					
R91	7.0	9.5	4.8	6.5	0.007
R91A					
77	7.5	11.5	4.5	8.5	0.004
N7	7.5	11.5	5.0	9.0	0.0025
4W7					
231	6.5	10.5	4.8	8.2	0.015
AU6	5.5 Av.		5.0 Av.		0.0035
AK5	3.4	4.4	2.45	3.25	0.020
AG5	5.2	7.8	1.3	2.3	0.025
SH7					
SH7L	6.8	10.2	4.9	9.1	0.003
2SH7					
SH7GT	6.8	10.2	4.9	9.1	0.004
2SH7GT					
36/1232	6.8	11.2	5.3	8.7	0.007
7	6.4	9.6	4.5	8.5	0.010

Type	Cin, μμf Min.	Cin, μμf Max.	Cout, μμf Min.	Cout, μμf Max.	Cgp, μμf max.
310A	4.7	7.1	11.0	19.0	0.013
328A					
6SJ7					
6SJ7Y	4.9	7.1	5.2	8.8	0.005
12SJ7					
6SJ7GT	5.7	8.3	5.6	9.4	0.005
12SJ7GT					
14C7	4.7	7.5	4.8	8.2	0.007
7C7	4.5	6.5	4.7	8.3	0.007
6J7	5.6	8.4	8.4	15.6	0.005
6J7GT	3.6	6.2	8.4	15.6	0.005
12J7GT					
6C6	4.0	6.0	4.6	8.4	0.007
1620	7.0 Av.		12.0 Av.		0.005
1603	4.6 Av.		6.5 Av.		0.007
57	4.3	5.7	5.6	7.4	0.007
6W7G	3.5	6.7	6.0	11.0	0.007
CK604A	5.0 Av.		3.6 Av.		0.030
1205 (SD673D)	5.4 Av.		4.4 Av.		0.003

Type	Cgk, μμf Min.	Cgk, μμf Max.	Cpk, μμf Min.	Cpk, μμf Max.	Cgp, μμf max.
713A	3.8	4.8	2.1	2.9	0.020
717A	4.3	5.3	2.7	3.5	0.025
6AS6	3.5	4.5	2.6	3.4	0.020
6AJ5	3.6	4.6	1.6	2.4	0.020
384A	2.4	3.4	1.7	2.5	0.030
385A	2.7	3.7	2.0	2.8	0.030
954	2.0	4.0	2.0	4.0	0.009
9001	2.9	4.3	2.1	3.9	0.010
77	4.1	5.3	9.7	12.3	0.007
6J7G	4.0	6.6	8.4	15.6	0.007

probably due in part to the use of a gold-plated grid. It is the most difficult to manufacture and the highest-priced of the three, and requires the least heater power. The 6AG5, while having a figure of merit about 20 per cent lower than that of the 6AK5, has the advantages of a higher plate-voltage rating, a higher plate dissipation, and a sharper cutoff. Both have two cathode connections for the isolation of input and output circuits. The 6AU6 was not produced in quantity until after the war, and was intended primarily for FM and television receivers and for general-purpose applications. Although its transconductance is about the same as that of the other two, it is obtained at the expense of considerably higher plate and screen currents. Unlike the other two, the 6AU6 does not have two cathode connections. The 6AK5 is perhaps the most widely used miniature tube in radar equipment, finding applications in high-frequency, wideband i-f, and video amplifiers, as a multivibrator or switch tube, and in other uses. It is also used as a triode, and occasionally even as a diode. The 6AG5 is used to a somewhat lesser extent for similar applications.

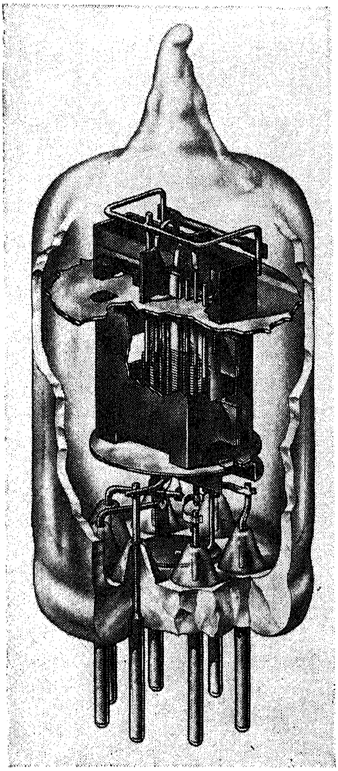


FIG. 14·15.—Miniature r-f pentode 6AS6.

The types of Group 19-8 (the 6SH7, etc.) are intended for high-frequency amplifiers. Although their transconductance and figure of merit are not so high as for the 6AC7 their other features make them preferable for such applications. These features include the use of two cathode leads, considerably less variation when operated under the same conditions, and very sharp grid cutoff characteristics. This last feature is often of advantage in multivibrator and switching applications.

The 713A and 717A of Group 19-10 are essentially earlier versions of the 6AK5 and appear to have no advantages over the latter.

The miniature 6AS6 (19-11) shown in Fig. 14·15, is essentially a 6AK5 with the suppressor grid brought out to a separate pin and with the structure so modified as to obtain a sharp g3 cutoff and comparatively high g3-to-plate transconductance. As a result the g1-to-plate transconductance is somewhat lower than that of the 6AK5, but the 6AS6 is the only American pentode with really sharp g3 cutoff characteristics. The

VR116 (19-12) has similar characteristics, and although not easily obtained in this country, is included because it is the only other type with this feature. The sharp g3 cutoff is of value in several radar applications, particularly in range unit and synchronizer circuits. Some of the pentagrid mixer and amplifier tubes can be used when good control on more than one grid is desired, and several pentodes other than the 6AS6 have g3 cutoff characteristics that may be satisfactory for certain applications. The values of grid bias for nominal plate-current cutoff for several pentodes are as follows:

Type	Group	Bias, Vdc on g3
6AS6	19-11	−15
SD828A	19-23	−50
EF50, VR91, VR91A	19-2	−60
7V7, 7W7, 14W7	19-3	−70

By comparison the 6AC7 requires a g3 voltage of −150 for nominal cutoff. More complete specifications are given in Table 19. The SD828A is a subminiature developmental type.

Of the pentagrid mixer and amplifier tubes several may be used to obtain good control from two grids. The transconductance of these types is usually less than would be desired, however. The 6L7 or 6L7G of Table 30 have g1-to-plate and g3-to-plate transconductances of about 1100 micromhos each, but g1 has remote-cutoff characteristics. The same thing is true of pentagrid converters such as the 6SA7 and 6A8 and other types of Tables 26 and 27, for which one of the two "control" grids has a remote cutoff.

The 6AJ5 (19-14) is a miniature sharp-cutoff pentode designed for operation at a plate and screen supply voltage of 28 Vdc, which can be obtained directly from the electrical system of a military airplane. Its characteristics at this low voltage are essentially the same as those of the 6AK5 at a much higher voltage. The transconductance of the 6AJ5 at 28 Vdc is about half that of the 6AK5 at 150 Vdc, but is remarkably high for operation at such a low voltage. A number of other tubes of various types have been or are being developed for 28-volt operation.

The tubes of Group 9-17 are general-purpose sharp-cutoff pentodes of modern design. They have excellent characteristics for all applications where high transconductance values are not required. The same is true of the loctal types 7C7 (19-20) and 14C7 (19-18). The types in Groups 19-21 and 19-22 have the same general characteristics but are of older design and may be considered obsolescent. The 1603 (19-22), however, is particularly suited to low-level audio stages because of its low noise and hum level.

The miniature 9001 and the acorn 954 of Group 19-19 were designed as r-f amplifiers at frequencies up to 400 Mc/sec. Although neither is of recent design, either one is probably as satisfactory as any other tube for narrow-band operation. For broadband operation such types as the 6AK5 or the 6AG5 are preferable.

Of the developmental types, the SD828A (19-23) is a subminiature pentode with characteristics suitable for general-purpose applications. Its ratings and characteristics are comparable to those of a full-sized tube, and it has a 300-volt heater-to-cathode voltage rating. It would be more generally useful if the suppressor grid were brought out. The SD828E is similar but has a higher transconductance and figure of merit. The exact values of its characteristics are not known. The CK604A is almost exactly the same as the 6AK5 but is made in a baseless T-4½ bulb. The A4481A and A4485 have higher transconductance than any other miniature or acorn tubes, and presumably also have very high figures of merit.

The characteristics of remote-cutoff and semiremote-cutoff pentodes are given in Table 20. The distinctions between these and the sharp-cutoff types have been discussed previously. In general they find their principal applications in broadcast and communications receivers where automatic gain control is used and the receivers are intended for the reception of amplitude-modulated signals. In such cases their use reduces the cross modulation encountered with signals of high intensity and in addition permits more satisfactory gain control circuits. They are little used in radar systems or in f-m receivers.

In many cases a remote- or semiremote-cutoff tube is the counterpart of one among the sharp-cutoff types, although usually the transconductance of the former will be lower at similar values of plate and screen currents. For example, the 6AB7 (20-1) is similar in construction and in many characteristics to the sharp-cutoff 6AC7. The 6SG7 (20-2) is similar to the 6SH7 (19-8), the 6BA6 (20-3) is much like the 6AU6 (19-5), and the 6SK7 (20-8) has its sharp-cutoff counterpart in the 6SJ7 (19-17).

The types in the first five groups of Table 20 are all of the semiremote-cutoff class with fairly high transconductance. Those in Group 20-2, such as the 6SG7, have two cathode leads for the isolation of input and output circuits in high-frequency operation. The 6BA6 and 12BA6 (20-3) are the only semiremote-cutoff miniature types in production.

The 7R7 and 14R7 (20-6) are loctal duo-diode pentodes with fairly high transconductance and figure of merit of the semiremote-cutoff section and are thus unique. Other duo-diode pentodes are listed in groups 20-16, 20-17, and 20-18, and the 6SF7 and 12SF7 of group 20-7 have a single diode in addition to the pentode section.

Group 15 lists remote-cutoff pentodes which have transconductances of about 2000, and which find wide application at moderate frequencies.

The 6SS7 (20-9) and the 7B7 (20-12) are similar but require only half the heater power.

The tubes in a number of the other groups of Table 20 are also much like those of Group 20-8 but are of older construction and may be considered obsolescent. They are listed in Groups 11, 14, 15, 16, 18, and 19.

The acorn 956 and the miniature 9003 (20-10) are very similar respectively, to the 954 and 9001 of Table 19. The 9003 is the only miniature remote-cutoff pentode made.

Of the developmental types the A4444C and the A4466B have the highest values of transconductance of any semiremote-cutoff pentodes listed. The 26A6 is intended for 28-volt operation like the 6AJ5, and is one of a new line of 28-volt tubes which also includes an output tube, the 26B5, a duo-diode medium-Mu triode, the 26C6, and a converter, the 26D6.

Audio Output and Small Transmitting Pentodes and Tetrodes.—The tube classified as output and small transmitting tubes are tetrodes and pentodes for which the most important design requirement is the ability to deliver an appreciable amount of power to the load circuit. This feature distinguishes them from the pentodes previously discussed, for which the most usual requirement is a large voltage gain at low power levels. In general, the output or "power" tubes have higher plate dissipation ratings and somewhat higher plate voltage ratings than the r-f amplifier pentodes. In most cases no attempt has been made to obtain very low values of plate to control grid capacitance since this is not required for the usual applications of power tubes. The value of this capacitance ranges from $\frac{1}{4}$ to about 1 $\mu\mu$f, or much larger than the same value for the r-f tubes.

The distinction between audio output and small transmitting tubes is largely arbitrary, and is made chiefly on the basis of the commonest uses for each type in the past. Most audio output tubes make fairly good low-powered transmitting oscillators or r-f amplifiers, and the converse is also true in many cases.

Undoubtedly the most common application of the tubes of Table 21 is in the output stage of a radio receiver or other audio amplifier, driving a loud-speaker or other electroacoustic device, but they may also be used for many other purposes. Many of them are used as crystal oscillators or frequency multipliers in the lower-powered stages of transmitters. In radar they are used for many applications where tubes of fairly high power capabilities are required, as in deflection-yoke drives for electromagnetic CRT circuits, in voltage regulators, and sometimes as video amplifiers.

Output pentodes and beam tetrodes are listed in order of decreasing plate dissipation in Table 21. Twin output tubes, of which there are

TABLE 20.—REMOTE- AND SEMIREMOTE-CUTOFF PENTODES

Group	Type	Ef, V	If, A	Maximum ratings Eb, Vdc	Ec2, Vdc	Pp, W	Pg2, W	Ehk, V	Test conditions Eb, Vdc	Ec2, Vdc	Ec1, Vdc	Ib, mAdc	Ic2, mAdc	gm, μmhos	Cutoff char. Ec1, Vdc	gm, μmhos Min.	gm, μmhos Max.	Limits of essential characteristics Ib, mAdc Min.	Ib, mAdc Max.	Ic2, mAdc Min.	Ic2, mAdc Max.	gm, μmhos Min.	gm, μmhos Max.	Ic1 μAdc max.	Emission test Eb, Vdc	Is, mAdc min.	Base	Bulb	Notes
1	6AB7	6.3	0.45	330	220	4.0	0.75	100	300	200	−3	12.5	3.2	5000	−15	5	140	9.5	15.5	2.3	4.1	4000	6000	−2.0	20	65	Oct	Metal	
2	6SG7	6.3	0.30	330	220	3.3	0.70	100	250	125	−1	11.8	4.4	4700	−14	10	100	9.0	14.6	2.9	5.9	3800	5600	−1.0	20	95	Oct	Metal	(2), (3)
	6SG7GT																										Oct	T-9	
	12SG7	12.6	0.15																								Oct	Metal	
3	6BA6	6.3	0.30	330	140	3.3	0.65	100	250	100	nn	11.0	4.2	4600	−20	50 Av.		....	....	....	...	....	....	.....	..	..	Min	T-5½	(4)
	12BA6	12.6	0.15																										
4	6SD7GT	6.3	0.30	330	140	4.4	0.44	100	250	125	−2	9.5	3.2	4250	−16	1	50	7.1	11.9	2.0	4.5	3400	5100	−1.0	20	95	Oct	T-9	
5	7H7	6.3	0.30	330	165	2.75	0.55	100	250	150	nn	10.0	3.2	4200	−19	5	70	8.0	12.5	2.0	4.5	3600	4800	−1.0	20	80	Loc	T-9	(5)
	14H7	12.6	0.15																										
6	7R7	6.3	0.30	300	110	2.2	0.30	100	250	100	−1	6.2	1.6	3400	−20	1	30	4.3	7.4	0.4	3.4	2650	3950	−1.0	20	70	Loc	T-9	(1), (2), (6)
	14R7	12.6	0.15																					−1.5					
7	6SF7	6.3	0.30	330	110	3.5	0.50	100	250	125	−3	13.5	3.6	2050	−45	1	30	10.2	16.8	2.4	4.8	1650	2450	−1.0	30	40	Oct	Metal	(2), (7)
	12SF7	12.6	0.15																										
8	6SK7	6.3	0.30	330	140	4.4	0.44	100	250	100	−3	9.2	2.6	2000	−35	1	30	6.5	12.0	1.6	3.4	1600	2400	−1.0	30	65	Oct	Metal	(8)
	6SK7GT/G																										Oct	T-9	
	7A7																			0.5	4.0						Loc	T-9	
	12SK7	12.6	0.15																	1.6	3.4						Oct	Metal	
	12SK7GT/G																										Oct	T-9	
	14A7/12B7																			0.5	4.0						Loc	T-9	

9	6SS7	6.3	0.15	330	140	2.25	0.35	100	250	100	−3	9.0	2.0	1850	−35	1	30	9.2	16.8	1.6	3.4	1800	2500	−1.0	30	45	Oct	Metal	(9)
10	956	6.3	0.15	275	110	1.8	0.33	90	250	100	−3	6.7	2.7	1800	−35	2	50	4.4	8.9	1.4	4.0	1300	2400	−1.0	15	20	Ac	Ac	(2), (10)
	9003																										Min	T-5½	(10)
11	6S7	6.3	0.15	330	110	2.4	0.27	100	250	100	−3	8.5	2.0	1750	−35	1	30	6.0	11.0	1.1	2.9	1450	2050	−1.0	30	40	Oct, TC	Metal	
	6S7G																										Oct, TC	ST-12	
12	7B7	6.3	0.15	330	110	2.5	0.27	100	250	100	−3	8.5	1.7	1750	−40	1	30	6.5	11.0	0.35	2.7	1450	2150	−1.0	30	50	Loc	T-9	
13	337A	10.0	0.32	275	150	2.5	0.40	150	135	135	−3	6.0	1.8	1725	−13.5	nn	nn	4.0	8.0	0.6	3.0	1350	2100	−0.5	..	...	6, TC	ST-12	(11)
14	6U7G	6.3	0.30	330	110	2.5	0.70	100	250	100	−3	8.2	2.0	1600	−40	1	30	6.0	10.9	1.0	3.5	1325	1900	−1.0	30	45	Oct, TC	ST-12	
	6D6																										6, TC	ST-12	
	58	2.5	1.00																					−0.5					
15	6K7	6.3	0.30	330	140	3.0	0.40	100	250	100	−3	7.0	1.7	1450	−35	1	30	4.9	9.1	0.9	2.4	1200	1700	−1.0	30	45	Oct, TC	Metal	
	6K7G																										Oct, TC	ST-12	
	6K7GT																										Oct, TC	T-9	
	78																			1.3	2.7						6, TC	ST-12	
	12K7GT	12.6	0.15																	0.9	2.4						Oct, TC	T-9	
16	6B8	6.3	0.30	275	140	2.5	0.33	100	250	125	−3	10.0	2.3	1325	−21	nn	nn	7.3	12.7	1.7	3.2	1050	1600	−1.0	30	25	Oct, TC	Metal	(1), (2), (13)
	12C8	12.6	0.15																										(1), (2), (13)
	VT153																												(1), (2), (10), (13)
17	7E7	6.3	0.30	300	110	2.2	0.40	100	250	100	−3	7.5	1.6	1300	−35	1	30	5.6	9.7	0.3	2.6	1075	1600	−1.5	30	40	Loc	T-9	(1), (2)
	14E7	12.6	0.15																										
18	6B8G	6.3	0.30	275	140	2.5	0.33	100	250	125	−3	9.0	2.3	1125	−21	nn	nn	6.6	11.4	1.7	2.9	900	1350	−1.0	30	25	Oct, TC	ST-12	(1), (2)
	6B7														......	......	......										7S, TC	ST-12	
	2B7	2.5	0.80																										
19	39/44	6.3	0.30	250	90	....	....	100	250	90	−3	5.8	1.4	1050	−30	5	40	4.5	7.0	0.7	2.0	900	1300	−1.0	30	45	5, TC	ST-12	(2)

TABLE 20.—REMOTE- AND SEMIREMOTE-CUTOFF PENTODES.—(*Continued*)

Group	Type	Ef, V	If, A	Maximum ratings					Test conditions						Cutoff char.			Limits of essential characteristics						Ic1 µAdc max.	Emission test		Base	Bulb	Notes
				Eb, Vdc	Ec2, Vdc	Pp, W	Pg2, W	Ehk, V	Eb, Vdc	Ec2, Vdc	Ec1, Vdc	Ib, mAdc	Ic2, mAdc	gm, µmhos	Ec1, Vdc	gm, µmhos		Ib, mAdc		Ic2, mAdc		gm, µmhos			Eb, Vdc	Is, mAdc min.			
																Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.						
Developmental types																													
20	A4444C	6.3	0.30	250	100	2.0	0.30	...	250	100	−1	7.0	2.0	7000	−15	20 Av.		....	....	....	...	....	....	.....	..	..	Min	T-5½	(2), (10)
21	A44CGB	6.3	0.30	Characteristics similar to those of A4444C.																							Ac	Ac	
22	26A6	26.5	0.07	Similar to 6BA6 and 12BA6 but for operation at Eb = 28 Vdc.																							Min	T-5½	

NOTE: All types in this table have heater-type cathodes. Heater-cathode leakage specifications are Ihk = 20 µAdc max for Ehk = 100 Vdc for all except the 6BA6 and 12BA6 and the developmental types, for which specifications are not given. Ehk = 100 Vdc max except for the 956 and 9003 (Ehk = 90 Vdc max) and the developmental types. The suppressor grid (g3) is brought out to a separate pin except as indicated by Note (2).

(1) Has two diodes with cathode common with pentode section. Diode ratings for all types are: I1b = I2b = 1 mAdc max. Test conditions are: E1b = E2b = 10 Vdc; I1s = 0.8 mAdc min, I2s = 0.8 mAdc min. For further information on diodes see Sec. 14.2 above.
(2) Suppressor grid internally connected to cathode.
(3) Has two cathode leads for high-frequency applications. Test condition for Ic max. Ec1 = −1.5 Vdc.
(4) Under "test conditions," Ec1 is obtained from 70-ohm cathode resistor.
(5) Also has ratings for 28-volt operation: Eb = Ec2 = 28 Vdc, Rk = 0, Rg1 = 2.0 megohms, gm = 1500 µmhos min, 2700 max. Under "test conditions" Ec1 is obtained from 180-ohm cathode resistor.
(6) Also has ratings for 28-volt operation: Eb = Ec2 = 28 Vdc, Ec1 = −0.75 Vdc, gm = 1100 µmhos min, 2100 max.
(7) Has single diode plate, cathode common with pentode, ratings and characteristics as in Note (1). Test conditions for this group are not typical operating conditions; note that test Ec2 exceeds maximum rating.
(8) Also has ratings for 28-volt operation: Eb = Ec2 = 28 Vdc, Rk = 0. Rg1 = 2 megohms, Ib = 1.3 mAdc min, 2.6 max. Ic2 = 0.35 mAdc min, 1.0 max. gm = 950 µmhos min, 1450 max.
(9) Limits of essential characteristics are for Ec1 = −1 Vdc; test condition for Ic1 max is Ec1 = −1.5 Vdc.
(10) Useful as an amplifier up to 400 Mc/sec.
(11) Cutoff characteristic: at Ec1 = −13.5 Vdc, Ib = 60 µAdc min, 400 max.
(12) The VT153 differs from the 1208 only in having a low-impedance lead welded between Pin 1 and the shell.
(13) Cutoff characteristic: at Ec1 = −21 Vdc, Ib = 70 µAdc max.

Interelectrode capacitances (remote- and semiremote-cutoff pentodes)

Type	Cin, $\mu\mu f$ Min.	Cin, $\mu\mu f$ Max.	Cout, $\mu\mu f$ Min.	Cout, $\mu\mu f$ Max.	Cgp, $\mu\mu f$ max.	Notes
6AB7	7.0	9.0	4.0	6.0	0.015	
6BA6 12BA6	5.5 Avg		5.0 Avg		0.0035	
7H7 14H7	6.5	9.5	5.5	8.5	0.007	
7R7 14R7	4.2	7.0	4.0	6.6	0.004	(1)
6SK7 12SK7	4.8	7.2	5.2	8.8	0.003	
6SK7GT/G 12SK7GT	5.2	7.8	5.6	9.4	0.005	
7A7 14A7/12B7	4.0	8.0	5.0	9.0	0.005	
6SS7	4.4	6.6	4.9	9.1	0.004	
6S7	5.3	7.7	7.9	13.1	0.005	

Type	Cin, $\mu\mu f$ Min.	Cin, $\mu\mu f$ Max.	Cout, $\mu\mu f$ Min.	Cout, $\mu\mu f$ Max.	Cgp, $\mu\mu f$ max.	Notes
6S7G	3.5	5.3	6.4	10.0	0.008	
7B7	3.5	7.0	4.0	8.0	0.007	
337A	4.7	7.1	11.0	19.0	0.013	
6U7G	4.1	5.9	6.7	11.3	0.007	
6D6	3.7	5.7	5.2	7.8	0.007	
58	3.7	5.7	4.4	8.2	0.007	
6B8	4.8	7.2	7.2	10.8	0.005	
12C8	6.0 Avg		9.0 Avg		0.005	
7E7 14E7	3.5	5.7	3.2	6.0	0.005	(2)
A4444C	5.3 Avg		2.3 Avg		0.005	

Type	Cgk, $\mu\mu f$ Min.	Cgk, $\mu\mu f$ Max.	Cpk, $\mu\mu f$ Min.	Cpk, $\mu\mu f$ Max.	Cgp, $\mu\mu f$ max.	Notes
6SG7 12SG7	6.8	10.2	4.9	9.1	0.003	
6SG7GT	6.8	10.2	4.9	9.1	0.004	
6SD7GT	7.2	10.8	6.0	9.0	0.004	
6SF7 12SF7	4.4	6.6	4.2	7.8	0.004	(3)
956	2.0	4.0	2.0	4.0	0.009	
9003	2.7	4.1	2.1	3.9	0.010	
6K7	5.8	8.2	9.0	15.0	0.005	
6K7G	4.0	6.6	9.0	15.0	0.007	
6K7GT 12K7GT	3.6	6.2	9.0	15.0	0.005	
78	3.9	5.1	9.7	12.3	0.007	
6B8G	2.9	4.3	7.0	12.0	0.010	
6B7	2.8	4.2	7.0	12.0	0.007	
2B7	2.5	4.5	7.0	12.0	0.007	
39/44	3.0	4.0	8.0	12.0	0.007	

NOTES: (1) Cg1-D1 = 0.005 $\mu\mu f$ max. Cg1-D2 = 0.002 $\mu\mu f$ max.
(2) Cg1-D1 = 0.013 $\mu\mu f$ max. Cg1-D2 = 0.003 $\mu\mu f$ max.
(3) Cg1-D = 0.002 $\mu\mu f$ max. Cp-D = 0.5 $\mu\mu f$ min, 1.1 max.

TABLE 21.—OUTPUT PENTODES AND BEAM TETRODES

Group	Type	Ef, V	If, A	Maximum ratings						Test conditions						Limits of essential characteristics						Ic μAdc max.	Leakage test, Ihk μAdc max.	Emission test		Base	Bulb	Notes
				Eb, Vdc	Ec2, Vdc	Pp, W	Pg2, W	Ib, mAdc	Ehk, V	Eb, Vdc	Ec2, Vdc	Ec1, Vdc	Ib, mAdc	Ic2, mAdc	gm, μmhos	Ib, mAdc Min.	Ib, mAdc Max.	Ic2, mAdc Min.	Ic2, mAdc Max.	gm, μmhos Min.	gm, μmhos Max.			Eb, Vdc	Is, mAdc min.			
1	6L6	6.3	0.90	400	300	21	2.75	...	200	250	250	−14	72	5	6,000	58	86	0	8	5200	6800	−3	75	50	275	Oct	Metal	
	6L6G																									Oct	ST-16	
	6L6GA																									Oct	ST-14	
	1614			375			3.50	110										0.1	8							Oct	Metal	(1)
	1622			330	275	15	1.50	...								62	82	0	8	5400	6600					Oct	Metal	(2)
	1631	12.6	0.45	400	300	17.5	2.75	...	100									0.5	8	.....	......					Oct	Metal	
2	6AR6	6.3	1.20	400	315	21	3.50	125	200	250	250	−22.5	77	5	5,400	55	100	0	8	4300	6500	−3	75	..	...	Oct	T-11	(3)
				630	315	21	3.50	60																				
3	6Y6G	6.3	1.25	220	150	14	2.00	...	300	200	135	−14	61	2.2	7,100	43	79	0	4.4	5800	8400	−3	75	30	180	Oct	ST-14	
	25C6G	25.0	0.30						...							....	.....	...	....	....	......	...	..	..	...			
4	6V6	6.3	0.45	350	310	13.2	2.20	...	100	250	250	−12.5	45	4.5	4,100	33	57	0	7.5	3000	5200	−2	50	30	100	Oct	Metal	
	6V6G																									Oct	ST-14	
	6V6GT/G																									Oct	T-9	
	7C5															32	60	1	8.5	3200	5300	−4				Loc	T-9	
	14C5	12.6	0.225																							Loc	T-9	
5	6F6	6.3	0.70	410	315	12.0	4.00	...	100	250	250	−16.5	34	6.5	2,500	25	46	4	8.5	2075	2925	−4	75	30	55	Oct	Metal	
	6F6G																									Oct	ST-14	
	6F6GT																									Oct	T-9	
	42																									6	ST-14	
	1621			300	300	7.9	1.90	...	...							....	.....	...	....	....	......	...	..	..	...	Oct	Metal	(2)
	1613			350	275	10.0	2.50	50	100							25	43	4	8.0	2075	2925	−3	..	50	175	Oct	Metal	(1)
	6AD7G	6.3	0.85	410	315	9.0	3.00	...	...							...	.....	...	....	....	......	...	..	..	...	Oct	ST-14	(4)
	2A5	2.5	1.75	410	315	12.0	4.00	...	100							25	46	4	8.5	2075	2925	−4	25	30	65	6	ST-14	

6	6U6GT	6.3	0.75	220	150	11.1	2.20	...	100	135	135	−13.5	55	4.0	6,200	41	69	0	7.5	4600	7800	−2	75	30	170	Oct	T-9	
	25L6																									Oct	Metal	
	25L6G	25.0	0.30												9,500	35	67	0.4	5.4	7100	12,000	−3	75	30	180	Oct	ST-12	
	25L6GT/G			220	125	11.0	1.40	...	100	200	110	− 8.0	50	2.0												Oct	T-9	
7	50L6GT																									Oct	T-9	
	50A5	50	0.15												8,250											Loc	T-9	
	50B5			125	125	6.0	1.40	...	100	110	110	− 7.5	49	4.0	7,500	....	....	...	....	....	......	...	..	..	..	Min	T-5½	
	1632	12.6	0.60	125	125	5.5	....	...	...						9,000											Oct	Metal	
8	59	2.5	2.00	275	275	....	....	...	100	250	250	−18.0	35	9.0	2,500	25	44	5	9	2075	2925	−2	25	50	125	7L	ST-16	
	6K6GT/G			350	315															1800	2800		20			Oct	T-9	
9	7B5	6.3	0.40			9.4	3.10	...	100	250	250	−18.0	32	5.5	2,300	23	45	3	8	2000	3000	−2	50	30	40	Loc	T-9	
	41			275	275															1800	2800		20			6	ST-12	
10	349A	6.3	1.00	275	275	9.4	3.10	...	60	250	250	−14.0	32	6.5	4,250	22	43	3.5	9.5	3500	5000	−2	50	...	..	Oct	ST-12	(5)
11	35L6GT	35	0.15	220	125	9.3	1.10	...	160	200	110	− 8.0	41	2.0	5,900	30	52	0.4	4.2	4400	7400	−3	75	20	90	Oct	T-9	
	35A5															28	55	0.5	4.2	4430	7380			30	140	Loc	T-9	
12	12A5	12.6/6.3	0.3/0.6	200	200	9.1	2.75	...	100	180	180	−25.0	45	8.0	2,400	32	60	1.0	16.0	1800	3100	−5	75	50	150	7S	ST-12	
13	6AG7	6.3	0.65	330	330	9.0	1.50	...	100	300	150	− 3.0	30	7.0	11,000	20	40	4.0	9.0	9200	14,200	−2	40	20	180	Oct	Metal	(6)
	6AK7/6AG7																	5.0	9.0							Oct	Metal	(6), (7)
14	89	6.3	0.40	275	275	.....	....	...	100	250	250	−25.0	32	5.5	1,800	....	....	...	....	....	......	...	..	..	..	6, TC	ST-12	
	89Y															24	42	3.0	8.0	1225	2275	−2	25	30	45			
15	47	2.5	1.75	275	275	.. ..	.	.	xx	250	250	−16.5	31	6.0	2,500	25	40	4.5	7.5	2200	3000	−2	xx	30	45	5	ST-16	(8)
	12A6			275	275											22	38	1.0	6.0	2200	3800	−2	100	30	65	Oct	Metal	
16	12A6GT	12.6	0.15			8.25	1.65	...	100	250	250	−12.5	30	3.5	3,000											Oct	T-9	
	14A5			300	300											....	....	...	....	....	......	...	..	..	..	Loc	T-9	
17	7A5	6.3	0.75	135	135	6.0	1.30	...	100	125	125	− 9.0	44	3.5	6,000	30	60	1.0	7.0	4600	7200	−4	50	30	140	Loc	T-9	
18	38	6.3	0.30	275	275	.....	....	...	100	250	250	−25.0	22	3.8	1,200	16.5	28	2.8	4.8	975	1450	−2	20	30	45	5, TC	ST-12	

TABLE 21.—OUTPUT PENTODES AND BEAM TETRODES.—(*Continued*)

Group	Type	Ef, V	If, A	Maximum ratings: Eb, Vdc	Ec2, Vdc	Pp, W	Pg2, W	Ib, mAdc	Ehk, V	Test conditions: Eb, Vdc	Ec2, Vdc	Ec1, Vdc	Ib, mAdc	Ic2, mAdc	gm, μmhos	Limits of essential characteristics: Ib, mAdc Min.	Ib, mAdc Max.	Ic2, mAdc Min.	Ic2, mAdc Max.	gm, μmhos Min.	gm, μmhos Max.	Ic μAdc max.	Leakage test, Ihk μAdc max.	Emission test: Eb, Vdc	Is, mAdc min.	Base	Bulb	Notes
	25A6																									Oct	Metal	
19	25A6GT	25.0	0.30	180	150	5.3	1.9	...	100	135	135	−20.0	37	8.0	2450	....	....	...	....	....	......	...	..	..	..	Oct	T-9	
	43															29	45	6.0	10.0	1950	2950	−2	75	30	75	6	ST-14	
20	311A	10.0	0.64	200	150	.....	....	...	150	135	135	−15.0	31	7.0	2900	22	40	4.0	10.0	2500	3300	−1	75	..	..	5, TC	ST-12	
	329A	7.5	0.85		160																							
21	6A4/LA	6.3	0.30	200	200	.....	....	...	xx	180	180	−12.0	22	3.9	2200	18	30	2.5	8.0	1800	3000	−2	xx	30	40	5	ST-14	(8)
22	293A	10.0	0.32	275	200	.....	....	...	100	180	180	−18.0	16	3.5	1175	13	19.5	2.0	5.0	1000	1350	−2	20	..	..	6	ST-14	
23	6G6G	6.3	0.15	330	330	3.0	0.75	...	100	180	180	− 9.0	15	2.5	2300	11	19	1.5	4.5	1840	2760	...	20	30	45	Oct	ST-12	
	6AK6				275		0.83		180									1.0	4.0	1900	2600			..	..	Min	T-5½	(9)
	Developmental types																											
24	26A5	26.5	0.30	50	50	2.0	0.5	...	...	26.5	26.5	− 4.5	20	2.0	......	Characteristics similar to one section of 26A7GT										Min	T-5½	
25	A4455	6.3	.....	Characteristics similar to 6AG7																						Min	T-5½	
26	A4450B	6.3	0.45	Characteristics similar to 6V6GT/G																						Min	T-5½	
	A4470	12.6	0.225																							Min	T-5½	
27	HD34	6.3	0.54	1000	300	.....	....	...	...	For pulsed operation. Typical operation: Eb = 1kVdc, Ec2 = 300 Vdc, Ec1 = −100 Vdc, Rl = 1250 ohms, Esig = 75 v peak, ib = 700 ma.																Min	T-5½	

NOTES: (1) Ratings are for Class C telegraph operation.
(2) "For applications requiring continuity of service."
(3) The first set of ratings is for Class A operation, the second for Class B. The 21-watt Pp rating applies only when the tube is air-blast-cooled. Cutoff characteristics: Ib = 1 mAdc max when Ec1 = −65 Vdc.
(4) Also contains a small medium-mu triode section.
(5) For leakage test Ehk = 60 Vdc. For all other types it is 100 Vdc.
(6) These types are somewhat similar to types listed under "Sharp-cutoff Pentodes," Table 19. Cutoff characteristics: Ib = 0.1 mAdc max. when Ec1 = −20 Vdc.
(7) Direct contact to shell is made through grounding ring as well as through Pin 1.
(8) Oxide-coated filament; all types in table except 47 and 6A4/LA have heater-type cathodes.
(9) For Ic1 test Eb = Ec2 = 300 Vdc, Ec1 = −25 Vdc.

TABLE 21*a*.
Interelectrode capacitances (output pentodes and beam tetrodes)

Type	Cin, μμf		Cout, μμf		Cgp, μμf	
	Min.	Max.	Min.	Max.	Min.	Max.
6L6 6L6G	10.0 Avg 11.5 Av.		12.0 Avg 9.5 Av.		0.4 Avg 0.9 Av.	
1614 1622	7.0	13.0	7.2	16.8	....	0.6
6AR6	8.5	13.5	5.0	9.2	0.4	0.9
6V6 6V6G	7.0	13.0	5.4	12.6	...	0.9
6V6GT/G	7.9	11.1	5.6	13.5	...	0.9
7C5 14C5	9.5 Avg		9.0 Avg		....	0.7
6F6	6.5		13.0		0.2 Avg	
6F6G	8.0		6.5		0.5	
1621	7.5		11.5		0.2	
25L6	16.0		13.5		0.3	
25L6GT/G	15.0		10.0		0.8	
50B5	13.0		6.5		0.5	
6K6GT/G	5.5		6.0		0.5	
7B5	7.4		8.0		0.8	
35L6GT	13.0		9.5		0.8	

Type	Cin, μμf		Cout, μμf		Cgp, μμf	
	Min.	Max.	Min.	Max.	Min.	Max.
6AG7 6AK7/6AG7	11.5	14.5	6.5	8.5	...	0.06
47	......		13.0 Avg		1.2 Avg	
12A6	7.0	11.0	6.5	11.5	...	0.60
12A6GT	5.0	11.0	5.6	11.5	...	0.60
14A5	6.8 Avg		7.0 Avg		0.4 Avg	
7A5	13.0		7.2		0.8	
38	3.5		7.5		0.30	
25A6	8.5		12.5		0.20	
6G6G	5.5		7.0		0.5	
6AK6	3.6		4.2		0.12	

Type	Cgk, μμf		Cpk, μμf		Cgp, μμf	
	Min.	Max.	Min.	Max.	Min.	Max.
1613	4.5	8.5	9.5	17.5	0.09	0.6
89Y	1.2	1.8	3.5	5.5	2.0	3.0

NOTE: The capacitances for the 89Y are for the triode connection, with g2 and g3 connected to p.

only a few types, are similarly listed in Table 22. The small transmitting tubes of Table 24 and the twins of Table 25 may be of use for the same general purposes as those of Tables 21 and 22 when higher voltage or dissipation ratings are required.

In all four of these tables the aligned-grid or "beam" tetrodes are not distinguished from the true pentodes, whether the latter are of beam construction or not. There are now very few nonbeam tetrodes. The beam tetrodes are very similar to the pentodes in characteristics and applications. The beam types, whether tetrodes or pentodes, tend to

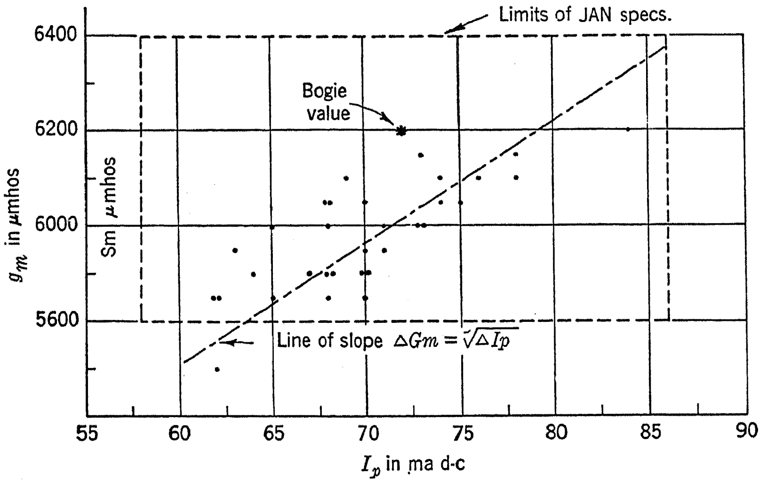


FIG. 14·16.—Variations in characteristics of 6L6GA tubes.

have higher values of transconductance, greater power sensitivity, and lower screen currents than nonbeam tubes of comparable size. In most cases, but with some important exceptions, the beam types are superior and of later design. In Table 21 the beam tubes are those in Groups 1, 2, 3, 4, 6, 7, 11, 16, 17, 24, 26, and 27. The nonbeam pentodes are in Groups 5, 8, 9, 10, 12, 13, 14, 15, 18, 19, 20, 21, 22, 23, and 25. Most of the latter will not be further discussed.

The tubes of Group 21-1, such as the 6L6, are the largest "receiving" beam tubes made, and are commonly used where tubes of their capacities are required. Most of the types in this group have the desirable characteristics of 200-volt heater-to-cathode voltage rating and closer tolerances on plate current and transconductance than any other types in the table. The actual variations found in a representative group of 6L6GA tubes tested under the conditions specified in the table are shown in Fig. 14·16. The 6L6, 6L6GA, and 6L6G are all identical in ratings and essential characteristics and differ only in mechanical construction and interelectrode capacitances. The 1614, 1622, and 1631 are somewhat

TABLE 22.—TWIN OUTPUT PENTODES AND BEAM TETRODES

Group	Type	Ef, V	If, A	Maximum ratings					Test conditions						Limits of essential characteristics						Ic1, μAdc max.	Leakage test, Ihk, μAdc max.	Emission test		Base	Bulb	Notes
				Eb, Vdc	Ec2, Vdc	Pp/p, W	Pg2/g2, W	Ehk, Vdc	Eb, Vdc	Ec2, Vdc	Ec1, Vdc	Ib/section mAdc	Ic2/section mAdc	gm/section μmhos	Ib/section, mAdc		Ic2/section, mAdc		gm/section μmhos				Eb = Ec2 = Ec1 Vdc	Is mAdc min.			
															Min.	Max.	Min.	Max.	Min.	Max.							
1	12L8GT	12.6	0.15	200	200	2.75	1.10	100	180	180	−9.0	13.0	2.8	2150	9.5	17.5	1.5	3.8	1850	2500	−2.0	40	30	40	Oct	T-9	
	1644																								Oct	T-9	(1)
2	28D7	28.0	0.40	100	67.5	3.0	0.50	100	28	28	−3.5	12.5	1.0	3400	8.0	17.5	0.2	2.2	2800	4800	−2.0	150	20	100	Loc	T-9	(2)
3	26A7GT	26.5	0.60	55	55	2.2	0.55	100	26.5	26.5	−4.5	20.0	2.0	5500	13.0	27.0	....	4.0	3500	6500	−2.0	100	10	70	Oct	T-9	
4	7G8/1206	6.3	0.30	330	110	1.65	0.11	100	250	100	−2.5	4.5	0.8	2100	2.5	6.5	0.15	1.3	1575	2625	−1.0	20	10	15	Loc	T-9	(2), (3)

NOTES: (1) The 1644 is selected for balance between sections.
(2) Maximum Ic1 is per section.
(3) The 7G8/1206 is not an output tube, being designed for r-f amplification up to 400 Mc/sec. It is a twin tetrode but is not a beam tube; it cannot be used for applications in which Ec2 can exceed Eb. Its cutoff characteristic is: Ec1 = −11.0 Vdc, Ib/section = 30 μAdc max.

Interelectrode Capacitances

Type	Cin, μμf		Cout, μμf		Cgp, μμf	
	min.	max.	min.	max.	min.	max.
12L8GT 1644	3.8	6.2	4.2	7.8	0.4	1.0
26A7GT	16.0 Av.		13.0 Av.		1.2 Av.	
7G8/1206	2.5	4.3	1.9	3.3	...	0.15

NOTE: The capacitances above are per section.

more specialized, the first having ratings as a transmitting tube, the second being selected for uniform characteristics and long life, and the last having a 12.6-volt heater. There have been manufactured from time to time various other variations of the same basic type, such as the 6L6GX, T21, and RK49, which are essentially 6L6G's with ceramic bases. There is a ruggedized version, the 6L6WGA, in development.

Some of the small transmitting beam tetrodes of Table 24 are also very similar to the 6L6. In particular the 807 (24-10) is almost identical with the 6L6 when tested under the same conditions. It differs, however, in that it has the plate connected to a top cap and has better internal insulation, both of which permit a higher plate-voltage rating, and has a lower grid-to-plate capacitance, a 5-pin low-loss base, a higher dissipation rating, and is rated for r-f power applications. The 1625 (24-10) is identical with the 807 except for its 12.6-volt heater. Other small transmitting tetrodes that are similar to the 6L6, though less so than the 807, are the 1624 (24-9) which is essentially an 807 with a filamentary cathode, and the 1619 (24-4) which is a metal 6L6, also with a filamentary cathode. These last two tubes have lower transconductances than their unipotential-cathode counterparts. The 350A (24-11) is also not unlike the 807, though its actual ratings and characteristics are considerably different.

The 6AR6 (21-2) is of interest because of its small bulb size in proportion to its plate dissipation and other ratings. Its maximum ratings apply only if the bulb is cooled with an air blast, however. This tube should find its application where space is at a premium.

The tubes in group 21-3 are designed to give high outputs at comparatively low values of plate voltage, operation at 135 Vdc being typical. One common use of the 6Y6G in radar equipment is as a voltage-regulator triode. Another somewhat similar tube is the 6U6GT (21-6), which has a lower maximum dissipation rating but a smaller bulb size. The 6Y6G has a 300-volt heater-to-cathode voltage rating, which is unique for tubes of its class.

The 6V6GT/G and the other tubes of Groups 21-4 are widely used small beam output tubes. While having lower maximum ratings, lower transconductance, and greater variation in essential characteristics than the tubes of the 6L6 group their small bulb size and low heater power make them very attractive for applications within their ratings. The miniature developmental tubes A4450B and A4470 (21-26) are very similar in characteristics to the 6V6 Group.

The types in Groups 21-7 and 21-11 were designed for use in transformerless radio receivers and are normally operated with supply voltages around 110 Vdc. They therefore have fairly large outputs for the low voltages at which they operate. They also have large values of transconductance. They have been little used in radar equipment since it is

seldom designed for transformerless operation, but are common in broadcast receivers. Group 21-7 includes a miniature type, the 50B5. The tubes of Group 21-11 have lower output but require less heater power.

The 6AG7 and the 6AK7/6AG7 (21-13) are pentodes rather than beam tubes and are unique in that they are the only output tubes designed primarily as video amplifiers. In many respects they are more like the sharp-cutoff pentodes of Table 19 than the output tubes. The construction of the 6AG7 is shown in Fig. 14·17. It may be considered a scaled-up 6AC7. These two tubes have very high values of transconductance, higher in fact than for any other tubes of this chapter, and a high figure of merit. Because of these characteristics they have found applications as multivibrators and in other circuits where a high transconductance and low capacitances are desired in a tube of moderately high power capabilities. They have also been used to a limited extent in r-f applications, particularly as frequency multipliers.

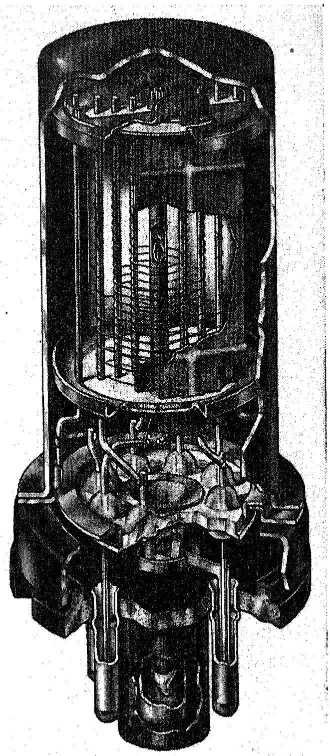


FIG. 14·17.—Video amplifier pentode 6AG7. (*Redrawn from picture furnished by Radio Corporation of America.*)

The figures of merit of a number of output and small transmitting tubes are given in Table 23.

The types in Group 21-16 are chiefly interesting for their low heater power requirements. They have been used principally in mobile equipment.

The 7A5 (21-17) is intended for operation at fairly low plate and screen voltages, and is in this respect similar to the 6Y6G (21-3).

The 6G6G and the 6AK6 (21-23) have the lowest heater power of any output tubes listed and therefore find application where this is an important consideration. Both are nonbeam pentodes.

The 26A5 (21-24) and the 28D7 (22-2) and 26A7GT (22-3) twins are intended for 28-volt operation. The first is still in the developmental status. All three have remarkable high outputs for such low plate voltages.

The developmental type HD34 (21-27) is a miniature beam tetrode intended for pulsed operation. The only other small beam tubes in these tables intended for such operation are the 3D21A (24-7) and the 3E29

(25-3). The last is essentially an 829B with ratings for high-voltage pulsed operation.

The 12L8GT and 1644 (22-1) are the only twin output tubes designed for operation at normally high voltages. Neither is widely used.

TABLE 23.—FIGURES OF MERIT OF OUTPUT AND SMALL TRANSMITTING TUBES

Type	Group	Figure of merit
6AG7	21-13	535
829B*	25-3	420
25L6GT/G	21-7	380
807,† 1625†	24-10	335
6AR6	21-2	300
6AK6	21-23	295
7A5	21-17	285
6L6G	21-1	285
6L6	21-1	275
35L6GT	21-11	260
2E22	24-12	260
6V6GT/G	21-4	240
1619	24-4	205
12L8GT*	22-1	195
26A7GT*	22-3	190
6G6G	21-23	185

* These types are twin tubes; the figures of merit will be the same for both sections in parallel as for one section since both transconductance and capacitances will be doubled.

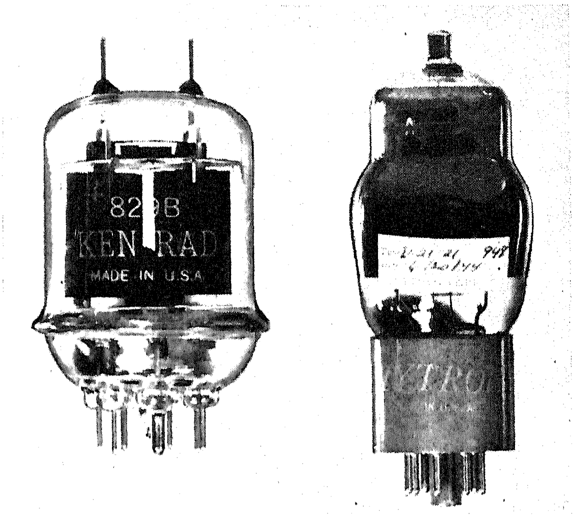
† The figure of merit given for the 807 and 1625 is for these tubes operated under the test conditions specified for the 6L6 in group 21-1.

The tubes listed in Tables 24 and 25 are all primarily intended for application as r-f power amplifiers and oscillators, although they may be suitable for other quite different purposes. One exception is the 3D21A (24-7), which is a pulsed modulator. Both beam types and nonbeam types are listed, the latter in Groups 2, 3, 6, 8, and 12 of Table 24. Because of the large number of characteristics given it has been necessary to split Table 24 into two parts, which has also been done in a somewhat different fashion with Tables 26 through 30 of the next section.

All of the nonbeam pentodes listed in Table 24 have Grid No. 3 characteristics such that they are suitable for suppressor-grid–modulated phone applications. The characteristics of many of these types, and of the beam transmitting tubes, have already been discussed. One interesting type not previously mentioned is the 2E30 (24-1), which has higher power-handling capabilities than any other miniature tube.

The twin beam transmitting tubes of Table 25 are intended as r-f power amplifiers at frequencies as high as 200 to 300 Mc/sec. The 829B in particular, however, is often used in wideband video amplifiers since it has a higher figure of merit than other types of a similar size. It is shown in Fig. 14·18, together with the 3D21.

Only those transmitting tubes with plate dissipations of 30 watts or less have been listed in the tables, since the larger types are almost never used for other than transmitting purposes and therefore cannot be considered "receiving" tubes.



(a) (b)

FIG. 14·18.—Small transmitting beam tetrodes. (a) 829B, Ken-Rad; (b) 3D21, Hytron.

From the standpoint of the uses of the Radiation Laboratory the following is a brief outline of the principal characteristics of interest for the most-used tetrodes and pentodes:

Tetrodes.—

6V6—General-purpose beam power amplifier. Useful in pulse circuits as amplifier, cathode follower, etc. Excellent r-f oscillator and a-f amplifier. Not as high gm or as good shielding between grid and plate as 6AG7. Large screen and plate dissipation for its size. Very rugged tube, uniform in manufacture.

6L6—Similar to 6V6 but higher voltage and current ratings. Useful as pulse amplifier and cathode follower. Large dissipation, high power gain. Useful as audio and servo power amplifier. Good series regulator tube when triode-connected.

807—Similar to 6L6 but with higher ratings and lower capacitances. Very rugged tube.

TABLE 24 PART 1.—SMALL TRANSMITTING PENTODES AND BEAM TETRODES

Group	Type	Ef, V	If, A	Maximum ratings												Test conditions							Base	Bulb	Cathode type
				Eb, Vdc	Ec3, Vdc	Ec2, Vdc	Ec1, Vdc	Pp, W	Pg3, W	Pg2, W	Ib, mAdc	Ic2, mAdc	Ic1, mAdc	Pi, W	Ehk, Vdc	Eb, Vdc	Ec3, Vdc	Ec2, Vdc	Ec1, Vdc	Ib, mAdc	Ic2, mAdc	gm, μmhos			
1	2E30 (HD59)	6.0	0.7	250	xx	250	.....	10	xx	...	60	..	...	....	xx	250	xx	250	−20	40	2.5	....	Min	T-5½	O
2	802	6.3	0.9	500	200	250	−200	10	2	6	60	..	7.5	25	100	500	0	225	−17	25	7.0	2500	7L, TC	ST-16	H
3	837	12.6	0.7	500	200	200	−200	12	5	8	80	..	8	32	100	500	0	200	−16	24	...	3400	7L, TC	ST-16	H
4	1619	2.5	2.0	400	...	300	−125	15	..	3.5	75	..	5	30	xx	300	0	300	−13.5	50	5.0	4500	Oct	Metal	O
5	65 / 2E25	6.0	0.8	450	...	250	−200	15	..	4	75	..	4.5	....	xx	450	0	250	−28	30	1.5	....	Oct, TC	T-10½	Th
6	307A	5.5	1.0	500	0	250	.....	15	..	6	60	25	...	....	xx	250	0	250	−20	50	4.0	4200	5, TC	ST-16	O
7	3D21A	12.6/6.3	0.85/1.7	3500	xx	850	.....	15	xx	3	...	..	...	....	150	600	xx	300	−30	32	2.0	5500	Oct, TC	ST-14	H
8	RK25	6.3	0.9	550	...	250	.....	16.5	..	6.5	60	45	...	....	100	250	0	250	−18	..	...	....	7L, TC	ST-16	H
9	1624	2.5	2.0	600	xx	300	−200	25	xx	3.5	90	..	5	54	xx	600	xx	300	−16.5	40	4.0	3600	5, TC	ST-16	O
10	807	6.3	0.9	600	xx	300	−200	25	xx	3.5	100	..	5	60	135	600	xx	300	−29	36	2.0	4200	5, TC	ST-16	H
	1625	12.6	0.45																				7L, TC	ST-16	H
11	350A	6.3	1.6	600	xx	300	−200	30	xx	4	105	..	5	62.5	150	250	xx	250	−18	62	4.0	6800	5, TC	ST-16	H
12	2E22	6.3	1.5	750	0	250	−200	30	..	...	100	20	...	....	xx	500	0	250	−15	60	4.0	5500	5, TC	ST-16	O

TABLE 24 PART 2.—SMALL TRANSMITTING PENTODES AND BEAM TETRODES

Group	Type	Limits of essential characteristics						Interelectrode capacitances					Ic1, μAdc Max.	Leakage test		Emission test		Notes
		Ib, mAdc		Ic2, mAdc		gm, μmhos		Cin, μμf		Cout, μμf		Cgp, μμf		Ehk	Ihk μAdc max.	Eb = Ec3 = Ec2 = Ec1, Vdc	Is, mAdc, min.	
		Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Max.						
1	2E30 (HD59)	..	..	...	...	....	....	10 Avg		5 Avg		0.50	...	xx	xx	..	...	
2	802	..	..	...	...	....	....	12		8.5		0.15	...	...	...	..	...	(1)
3	837	15	33	...	...	....	....	13	19	7.5	12.5	0.20	−5	100	100	30	130	(2)
4	1619	36	64	0	8	4000	5000	9.6 Avg		12.5 Avg		0.29	−5	xx	xx	50	200	
5	65	20	40	0	3	....	....	7.9	10.3	6.2	8.2	0.18	−2	xx	xx	50	140	(3)
	2E25	..	..	...	...			8.5 Avg		6.0 Avg		0.15	...			..	...	
6	307A	35	65	0	7	3400	5000	13	19	9	15	1.00	−5	xx	xx	50	125	(4)
7	3D21A	13	45	0	4	4000	7000	13	21	10	15	1.00	−5	100	175	..	...	(5)
8	RK25	..	..	...	...	....	....	10	16	10	18	0.20	...	...	...	..	...	
9	1624	28	52	0	7.5	3000	5000	8	14	5.5	9.5	0.25	−4	xx	xx	50	200	(6)
10	807	24	48	0	4	....	....	10	14	5.3	8.7	0.20	−4	100	100	50	300	(7), (8)
	1625					5100	6900											(7), (9)
11	350A	45	80	0	7	5500	8200	13.5	19	6.1	9.9	0.30	−7	100	125	..	...	(10)
12	2E22	42	78	0.5	6.5	4200	6800	11.5	15.5	5.8	9.3	0.20	−5	xx	xx	50	250	(11)

NOTES: (1) Maximum ratings for Class A operation: Pp = 15 W, Pg2 = 3 W.
(2) For max. Ic1 test adjust Ec1 so that Ib = 36 mAdc. For g3 cutoff test Ec3 = −145 Vdc, Ib = 2 mAdc min, 12 max.
(3) The 65 has been superseded by the 2E25.
(4) For the emission test Ef = 5.0 V. For g3 cutoff test Ec3 = −90 Vdc, Ib = 0 min, 15 mAdc max.
(5) The maximum ratings in the table are for grid-pulsed operation. Additional maximum ratings are Ec1 = 220 v, Pg1 = 0.5 W, pulse length = 10 μsec, typical ib = 8 amp. For g1 cutoff test Ebb = 4000 Vdc, Ec2 = 800 Vdc, Ec1 = −150 Vdc, Rp = 2 megohms, Ib = 300 μAdc max.
(6) Limits of gm are for Ec1 adjusted so that Ib = 48 mAdc at Eb = 300 Vdc.
(7) Maximum Ib for class-B audio applications is 120 mAdc. The characteristics of the 807 and the 1625 are nearly identical with those of the 6L6 when operated under the same conditions.
(8) For g1 cutoff test Ec1 = −100 Vdc, Ib = 0.5 mAdc max.
(9) Limits of gm are for Eb = 250 Vdc, Ec2 = 250 Vdc, Ec1 = −14 Vdc.
(10) For audio applications Ib = 125 mAdc max.
(11) For g3 cutoff test, Ec3 = −170 Vdc, Ib = 0 min, 10 mAdc max.

TABLE 25.—SMALL TWIN TRANSMITTING PENTODES AND BEAM TETRODES

Group	Type	If, A	Maximum ratings (Values are total for both sections) Eb, Vdc	Ec2, Vdc	Ec1, Vdc	Pp, W	Pg2, W	Ib, mAdc	Ic1, mAdc	Pi, W	Test conditions Eb, Vdc	Ec2, Vdc	Ec1, Vdc	Ib/p, mAdc	Ic2/section, mAdc	Limits of essential characteristics Ib/p, mAdc Min.	Ib/p, mAdc Max.	Ic2/section, mAdc Min.	Ic2/section, mAdc Max.	Ic1/section, μAdc, max.	Leakage test, Ihk, μAdc, max.	Emission test, Is/section, mAdc, min.	Base	Bulb	Notes
1	832A	0.8/1.6	750	250	−100	15	5	90	6	36	250	135	−10	30	3	18	42	0.1	5.5	−2	100	80	Spec. 7, 2TC	T-16	(1), (2)
2	815	0.8/1.6	400	225	−175	20	4.5	150	7	60	200	135	−10	35	3	23	47	0	6.0	−1	50	130	Oct, 2TC	T-16	(2), (3)
3	829B	1.12/2.25	750	225	−175	40	7	240	15	120	250	175	−11	60	5	38	82	0	10.0	−4	175	250	Spec. 7, 2TC	T-16	(2), (4)
	3E29		The 3E29 is identical with the 829B but also has ratings for pulsed operation.																						

NOTES: All four types have center-tapped 12.6/6.3-volt heaters, Ehk ratings of 100 Vdc max, and the leakage test is made at 100 Vdc. The emission test is made with Eb = Ec2 = Ec1 = 25 Vdc.

(1) For Ic1 test Eb = 400 Vdc, Ec2 = 250 Vdc, Ec1 is adjusted so that Ib = 19 mAdc.

(2) Maximum frequency for specified input ratings is 200 Mc/sec for the 832A and 829B, 125 Mc/sec for the 815. All are usable at somewhat higher frequencies at reduced inputs.

(3) Average gm/section and limits of gm/section are for Eb = 400 Vdc, Ec2 = 200 Vdc, Ec1 adjusted to make Ib = 25 mAdc. For Ic1 test the same conditions are specified. Average gm = 4000 μmhos, limits are 3200 μmhos min, 4800 max.

(4) Approximate gm/section = 9000 μmhos for Eb = 300 Vdc, Ec2 = 200 Vdc, Ec1 adjusted so that Ib = 60 mAdc.

Interelectrode capacitances in μμf

Type	Cin/section Min.	Cin/section Max.	Cout/section Min.	Cout/section Max.	Cgp/section max.	Cg2-k avg
832A	6.2	9.4	2.8	4.8	0.06	65
815	11.0	15.6	6.4	10.6	0.22	..
829B	12.8	16.2	5.2	8.7	0.10	65

3D21—Similar to 807 but physically smaller. Designed as a pulse tube, used mainly as a modulator and driver in radar sets. Will stand 4 kVdc on plate and very large currents.

6Y6G—Similar to 6L6 but will take very large currents at low plate voltages. Good blocking oscillator, excellent series regulator tube.

829—Essentially two 807's in one envelope. Primarily designed as uhf oscillator and amplifier but sometimes used as output stage in video amplifier.

Pentodes.——

6SJ7—General-purpose receiving pentode. High gain at low currents. Useful as audio voltage amplifier. Sharp cutoff. Uniform characteristics. Can be used in suppressor-control circuits. Very high gm (2500) and rp (over 1 megohm). Low grid current.

6SH7—Like 6SJ7 but higher gm and very sharp cutoff.

6SK7—Like 6SJ7 but with remote-cutoff control grid. Useful in AVC circuits and in devices where a parabolic control characteristic is required.

6AC7—High-performance i-f and video pentode. Very high gm (10,000), moderate input, g3 cutoff about −100 Vdc. Useful in video amplifiers, pulse generators, cathode followers, amplitude selectors, limiters, etc.

6AK5—Miniature i-f and video pentode, slightly better performance in i-f and video circuits than 6AC7 because of higher figure of merit. Low heater power, sharp cutoff. Generally useful in pulse circuits.

6AG5—Practically same as 6AK5 but higher capacitances and higher dissipation ratings.

6AG7—High-performance video pentode. Very high gm (10,000), moderate capacitances. Essentially a large 6AC7. Useful as video deflection amplifier, blocking oscillator for extremely rapid rates of rise, and as cathode follower to drive coaxial cable.

VR91—British equivalent of 6AC7 in nearly all respects.

VR65—(Not listed in tables.) British equivalent of 6SH7.

CV9—British, not listed in tables. Like 6AG7 but higher dissipation and gm.

6AS6—Similar to 6AK5 but with sharp g3 cutoff (−10 Vdc). Used as a time selector and in regenerative circuits of the "negative transconductance" variety in transitron, phantastron, etc. Only American equivalent of VR116.

VR116—British tube most used in time-selector and negative transconductance devices. Prototype for phantastron, sanatron, etc. High gm, low capacitances, large plate and screen dissipations.

14·5 Converters and Mixers.—The converter and mixer tubes of this section are vacuum tubes of relatively complicated structures, used pri-

TABLE 26.—PENTAGRID CONVERTERS (CLASS 1)

Tubes of this class have the following structure: g1, oscillator grid; g2, oscillator plate; g3 and g5 (internally connected), screen; g4, signal input grid.

All types in this table have the following characteristics in common:

Maximum ratings: Eb = 330 Vdc; Ec2 = 220 Vdc; Ec3 + 5 = 110 Vdc; Pp = 1.0 W; Pg2 = 0.75 W; Pg3 + 5 = 0.3 W; Ik = 15 mAdc; Ehk = 100 Vdc, at which Ihk = 20 μAdc max.

Test conditions: Eb = 250 Vdc; Ec2 = 250 Vdc; Ec3 + 5 = 100 Vdc; Ec4 = −3 Vdc; Ec1 = 0 with input signal adjusted to 18 Vac; Rg1 = 50,000 ohms; Rg2 = 20,000 ohms, Sc = 550 μmhos.

Emission test is made with all elements except the cathode at 30 Vdc.

Group	Type	Ef, V	If, A	Test conditions: Ib, mAdc	Test conditions: Ic2, mAdc	Test conditions: Ic3 +5, mAdc	Test conditions: Ic1, mAdc	Test conditions: Ik, mAdc	Cutoff char.: Ec4, Vdc	Cutoff char.: Sc, μmhos av.	Ib, mAdc Min.	Ib, mAdc Max.	Ic2, mAdc Min.	Ic2, mAdc Max.	Ic3 + 5, mAdc Min.	Ic3 + 5, mAdc Max.	Ik, mAdc Min.	Ik, mAdc Max.	Ic1, mAdc Min.	Ic1, mAdc Max.	Sc, μmhos Min.	Sc, μmhos Max.	Ic4, μAdc, max.	Emission test Is, mAdc, min.	Base	Bulb	Notes
1	6A8	6.3	0.30	3.5	4.0	2.7	0.4	10.6	−35	6	2.3	4.9	2.6	5.6	1.1	4.3	7.8	13.5	0.3	0.6	325	750	−2.0	40	Oct, TC	Metal	
	6A8G																								Oct, TC	ST-12	
	6A8GT																								Oct, TC	T-9	
	6A7																								7S, TC	ST-12	
	7B8																7.8	12.8			360	750	−1.5	65	Loc	T-9	(1)
	12A8GT	12.6	0.15														7.8	13.5			325	750	−2.0	40	Oct, TC	T-9	
	14B8																7.8	12.8			360	750	−1.5	65	Loc	T-9	(1)
	2A7	2.5	0.80														7.8	13.5			325	700	−2.0	40	7S, TC	ST-12	
2	6D8G	6.3	0.15	3.5	4.3	2.6	0.4	10.8	−35	6	2.6	5.6	...	...	1.0	4.2	7.5	13.5	0.3	0.6	325	750	−2.0	40	Oct, TC	ST-12	
3	7A8	6.3	0.15	3.0	4.2	3.2	0.4	10.8	−30	2	2.0	4.2	2.8	6.0	1.2	5.0	8.0	13.0	0.3	0.6	360	750	−1.5	50	Loc	T-9	(1), (2)

The oscillator sections have the following characteristics (not oscillating):

Group	Eb, Vdc	Ec4, Vdc	Ec3 + 5, Vdc	Ec2, Vdc	Ec1, Vdc	g1-g2 transconductance, μmhos min.	g1-g2 transconductance, μmhos max.	Ic2, mAdc, avg	Mu
1	250	−2	55	100	−1	1150 Av.		. .	. .
2	180	−0.5	55	180	0	850	1550	. .	. .
3	250	0	100	180	0	1600 Av.		10	65

NOTES: (1) The maximum rated value of Ic1 is 0.5 mAdc.
(2) The 7A8 is an octode: the suppressor grid g6 is internally connected to the cathode.

Interelectrode capacitances in $\mu\mu f$

Type	Cg4—all others (Cin)		Cp—all others (Cout)		Cg4-p, max.	Cg4-g2, avg	Cg4-g1, avg	Cg1-g2, avg	Cg2—all except g1, avg	Cg1—all except g2, avg	Cg2—all others, avg	Cg1—all others, avg
	Min.	Max.	Min.	Max.								
6A8	10.0	14.0	9.0	15.0	0.09	0.10	0.09	0.8	5.0	6.5	. . .	. . .
6A8G 6A8GT 12A8GT	7.8	11.2	9.0	15.0	0.35	0.19	0.16	1.1	4.6	6.0	. . .	. . .
2A7 6A7	6.4	10.6	6.8	11.2	0.30	0.15	0.15	1.0	. . .	. . .	5.5	7.0
7B8 14B8	7.5	12.5	6.7	11.3	0.25	0.2 max.	0.2 max.	0.9	3.4	5.0	. . .	. . .
6D8G	6.2	9.4	7.5	14.5	0.28	0.20	0.16	1.1	4.6	5.5	. . .	. . .
7A8	6.0	9.0	6.7	11.2	0.20	0.15 max.	0.15 max.	0.6	3.4	3.8	. . .	. . .

TABLE 27.—PENTAGRID CONVERTERS (CLASS 2)

Tubes of this class have the following structure: g1, oscillator grid; g2 and g4 (internally connected) screen and oscillator plate; g3, signal input grid; g5, suppressor grid.

All types in the following table have the following characteristics in common:

Maximum ratings: Eb = 330 Vdc; Ec2 + 4 = 110 Vdc; Pp = Pg2 + 4 = 1.1W; Ik = 15.5 mAdc; Ehk = 100 Vdc, at which the leakage current Ihk = 20 μAdc max; Ic3 = -2 μAdc max. These ratings are not given for group 1, and Ihk and leakage ratings are not given for group 3. Maximum Ic1 = 0.5 mAdc for group 4.

Test conditions: Eb = 250 Vdc; Ec2 + 4 = 100 Vdc, Ec1 = 0 (signal Eg1 is adjusted to make Ic1 = 500 μAdc max except for group 2); Rg1 = 20,000 ohms.

Group	Type	Ef, V	If, A	Test conditions: Ec3, Vdc	Ib, mAdc	Ic2 + 4, mAdc	Ik, mAdc	Sc, μmhos	Cutoff char.: Ec3, Vdc	Sc, μmhos Min.	Sc, μmhos Max.	Limits of essential characteristics: Ib, mAdc Min.	Ib, mAdc Max.	Ic2+4 mAdc Min.	Ic2+4 mAdc Max.	Sc, μmhos Min.	Sc, μmhos Max.	Emission test: Eb Vdc	Is mAdc min.	Base	Bulb	Notes
1	6SB7Y	6.3	0.30	−1.5	4.0	8.5	13.0	880	−20	10 Av.		. . .	. . .	. . .	. . . .	. . .	. . .	. .	. .	Oct	Metal	
2	7Q7	6.3	0.30	−2.0	3.5	8.5	12.5	550	−35	0	25	2.3	4.9	3.5	13.5	360	750	20	90	Loc	T-9	(1)
	14Q7	12.6	0.15																			
3	6BE6	6.3	0.30	−1.5	3.0	7.1	10.6	475	−30	4 Av.		. . .	. . .	. . .	. . . .	. . .	. . .	. .	. .	Min	T-5½	
	12BE6	12.6	0.15																			
4	6SA7	6.3	0.30	−2.0	3.5	8.5	12.5	450	−35	0.5	25	2.5	4.5	6.5	11.5	300	600	30	70	Oct	Metal	
	6SA7GT/G																			Oct	T-9	
	12SA7	12.6	0.15																	Oct	Metal	
	12SA7GT/G																			Oct	T-9	
	12SY7																			Oct	Metal	(2)
	12SY7GT																			Oct	T-9	(2)
	Developmental type																					
5	26D6	26.5	0.70	Characteristics similar to 6SA7, Group 4.																Min	T-5½	

The following characteristics apply to the oscillator section in the nonoscillating conditions: Eb = Ec2 + 4 = 100 Vdc; Ec1 = Ec3 = Ec5 = 0. Signal applied to g1 only.

Group	Gm, μmhos			Ik, mAdc, avg
	min.	avg	max.	
1	....	7700	....	35
2	4400	5500	....	30
4	3500	4500	5900	..

NOTES: (1) For group 1 under "test conditions" signal voltage Ec1 = 10 Vac. There is also a test for Ic1; Rg1 = 50,000 ohms, Ec3 = 0, Ic1 = 0.17 mAdc min, 0.3 max.

(2) The 12SY7 and 12SY7GT have ratings for 28-volt operation: Eb = Ec2 + 4 = 28 Vdc, Ec1 = 0, Ec3 = −1 Vdc, adjust signal voltage Eg1 so that Ic1 = 120 μAdc; Sc = 200 μmhos min, 400 max.

Under "emission test," Eb is the voltage applied to all elements except h and k.

Interelectrode capacitances in μμf

Type	Cin,		Cout,		Cg3-p,
	Min.	Max.	Min.	Max.	Max.
7Q7 14Q7	6.7	11.3	6.4	10.6	0.30
6BE6 12BE6	7.2 Av.		8.6 Av.		0.30
6SA7 12SA7 12SY7	7.6	11.4	8.4	15.6	0.13
6SA7GT/G 12SA7GT/G 12SY7GT	8.8	13.2	7.7	14.3	0.50

Cin above is Cg3—all others; Cout is Cp—all others.

Type	Cg1-g3, max.	Cg1-p, max.	Cg1—all others, avg	Cg1—all except k, avg	Cg1-k, avg	Ck—all except g1, avg
7Q7 14Q7	0.20	0.15	7.0	5.0	2.2	6.0
6BE6 12BE6	0.15	0.05	5.5	2.7	2.8	15.0
6SA7 12SA7	0.15	0.06	7.0	4.4	2.6	5.0
6SA7GT/G 12SA7GT/G	0.40	0.20	8.0	5.0	3.0	14.0

6SA7GT, 12SA7GT, 6BE6, and 12BE6 have g5 internally connected to k.

marily for frequency conversion in superheterodyne receivers. Five classes of these tubes may be distinguished: two different classes of pentagrid converters, listed in Tables 26 and 27; triode-hexode and triode-heptode converters, listed in Tables 28 and 29; pentagrid mixers, listed in Table 30. Because of the large number of characteristics of each type and the small number of types per class, the tabular form of the other tables of this chapter could not be used, and the five tables of this section have accordingly been considerably modified. Essentially the same kinds of data are presented here as for the other classes of tubes, however.

Pentagrid Converters.—Pentagrid converters are tubes with five concentric grids successively surrounding the cathode and a plate around the outermost grid. They are of two main classes. The first and earlier class, listed in Table 26, uses the cathode and the first two grids as an oscillator, Grid No. 2 acting as the plate. It is actually two rods without the usual spiral grid wires. Grids No's. 3 and 5 are internally connected and serve to screen the signal-input grid (No. 4) from the oscillator section and the plate. All tubes of this type are restricted as to operating potentials by the usual requirement of a nonbeam tetrode that the plate must never become negative with respect to the screen, except for the 7A8 (26-3) which is actually an octode, having a sixth grid internally connected to the cathode.

The second class of pentagrid converters, listed in Table 27, have a structure in which the first grid is the oscillator grid, as before, and the second functions both as the oscillator plate and as a screen between the oscillator section and the signal Grid No. 3. This structure requires that g2 be grounded for radio frequency, and the circuit thus becomes a grounded-plate oscillator. The fourth grid is connected internally to g2 and screens the signal grid from the remainder of the mixer section. The fifth grid is the suppressor.

Tubes in this second class of pentagrid converters are superior to those of the first class in two respects. Their much higher oscillator-section transconductance gives far better performance at high frequencies, and the use of a suppressor grid results in a considerably higher plate resistance with less resultant loading of the output transformer. Either class may be used with a separate oscillator tube, and they are often so used at the higher frequencies. All of these pentagrid converters may be used for other applications where a tube with two separate grids of good control characteristics is required. This type of operation has been discussed previously in connection with the 6AS6.

The types listed in groups 27-2, 27-3, and 27-4 are basically similar and are probably more frequently used than any other class of converter. The 6BE6 and 12BE6 (27-3) are the only miniature converters in quantity

TABLE 28.—TRIODE-HEXODE CONVERTERS

Type	Ef, V	If, A	Base	Bulb
6K8	6.3	0.30	Oct, TC	Metal
6K8G			Oct, TC	ST-12
6K8GT			Oct, TC	T-9
12K8	12.6	0.15	Oct, TC	Metal
12K8Y*			Oct, TC	Metal

* The 12K8Y has a low-loss base.

The interelectrode capacitances are as follows:

Type	Cin, $\mu\mu f$		Cout, $\mu\mu f$		Cgp, $\mu\mu f$ Max.
	Min.	Max.	Min.	Max.	
6K8 12K8 12K8Y	5.4	7.8	2.6	4.4	0.03
6K8G	3.7	5.5	3.5	5.5	0.08
6K8GT	4.0	6.0	3.3	5.3	0.08

NOTE: Cin is the capacitance between hexode g3 and all other electrodes; Cout is from hexode plate to all other elements: Cgp is the capacitance between hexode g3 (the signal grid) and hexode plate.

Other capacitances are as follows:

Capacitance, $\mu\mu f$	Type	
	6K8 12K8	6K8G 6K8GT
Hexode g3 to triode plate, max	0.02	0.05
Hexode g3 to hexode and triode g1, max	0.2	0.2
Hexode and triode g1 to triode plate, avg	1.1	1.8
Hexode and triode g1 to hexode plate, max	0.10	0.15
Triode plate to all except triode and hexode g1, avg	3.2	3.4
Triode and hexode g1 to all except triode plate, avg	6.0	6.5

All five types belong to one group and have the following characteristics:

Maximum ratings:

For the triode section, Eb = 140 Vdc, Pp = 0.75 W.

For the hexode section, Eb = 330 Vdc, Ec2+4 = 165 Vdc, Pp = 0.75 W, Pg2+4 = 0.70 W.

Ik = 16 mAdc, Ehk = 100 Vdc.

Test conditions:

For the triode section, Eb = 100 Vdc, Ib = 3.8 mAdc.

For the hexode section, Eb = 250 Vdc, Ec2+4 = 100 Vdc, Ec3 = −3 Vdc, Ib = 2.5 mAdc, Ic2+4 = 6.0 mAdc.

For both, Ec1 = 0, Rg1 = 50,000 ohms, the input signal to the g1's is adjusted to that Icl = 150 μAdc, and the conversion transconductance Sc = 350 μ mhos.

Cutoff characteristic: for hexode Ec3 = −30 Vdc Sc = 2 μmhos av.

Limits of essential characteristics:

Hexode Ib = 1.6 mAdc min, 3.6 max; Ic2+4 = 3.6 mAdc min, 9.0 max.

Ik = 9.5 mAdc min, 15.5 max; Sc = 230 μmhos min, 490 max.

Hexode Ic3 = −2 μAdc max.

For the h-k leakage test, Ihk = 20 μAdc max when Ehk = 100 Vdc.

For the emission test, with all elements except heater and cathode at 30 Vdc, Is = 70 mAdc min.

The oscillator section transconductance (not oscillating) is 2200 μmhos min, 4000 max, with triode Eb = 100 Vdc, Ec1 = 0, and hexode Ec2+4 = 55 Vdc and Ec3 = −0.5 Vdc.

With the oscillator section oscillating the triode and hexode Ic1 = 110 μAdc min, 220 max.

production at present. The developmental 26D6 (27-5) is designed for 28-volt operation.

Triode-hexode Converters.—The third basic class of converters is the triode-hexodes of Table 28.

These tubes may be considered as essentially pentagrid mixers of the first type with a separate triode oscillator section since the hexode section is similar to a pentagrid converter of the 6A8 type with the rods forming the oscillator plate omitted. This comparison is not strictly accurate since the triode-hexodes employ beam-forming shields which give a high plate resistance without the use of a suppressor grid. The triode control grid and the hexode No. 1 grid are actually one electrode in which the portion on one side of the cathode serves as the triode grid while the opposite portion furnishes the oscillator input to the hexode. These tubes are intended to give good performance at the higher frequencies. Unfortunately none is of the single-ended construction, all having top-cap connections to the signal grid.

Triode-heptode Converters and Pentagrid Mixers.—These last two classes will be described together, since the former is essentially the same as the latter plus a separate but internally connected triode oscillator section. They are listed in Tables 29 and 30.

Pentagrid mixers and triode-heptode converters are basically different from the other three classes of converters in that the signal input is impressed on the first grid rather than on the third and fourth as in the other types. This feature is intended to give better isolation between the oscillator and signal-frequency circuits. The other grids function as follows: g2 and g4 are internally connected and act as the screen; g3 is the oscillator input grid; g5 is the suppressor grid. In the triode-heptodes the oscillator grid is internally connected to the heptode g3, and for the pentagrid mixers an external oscillator is similarly connected either directly or through a condenser. The oscillator-section transconductance of the triode-heptodes is considerably lower than that obtainable with separate triodes or than the oscillator-section transconductance of the triode-hexodes or the second class of pentagrid converters.

The conversion transconductance of the 7S7 and 14S7 (29-3) is appreciably higher than for any other tubes of this section.

The pentagrid mixers of Table 30 are all essentially the same, the 1612 being a 6L7 selected for quiet operation in audio circuits. Several of the tube manufacturers who do not list the 1612 will furnish similarly selected 6L7's without changing the tube numbers. Pentagrid mixers are often used for other than r-f applications, such as d-c–controlled audio mixers and volume-expanding or -compressing amplifiers, where a tube with good control characteristics on two grids is required. The first grid has a remote cutoff characteristic, which may be a disadvantage in some

TABLE 29.—TRIODE-HEPTODE CONVERTERS

The following characteristics are common to all types in this table:

Heptode Eb = 330 Vdc max, Ec2 + 4 = 110 Vdc max. Ehk = 100 Vdc max, at which voltage Ihk = 20 μAdc max Heptode Ic1 = −1.5 μAdc max. For the triode section, the test conditions are Ebb = 250 Vdc, Ec1 = 0 with the signal voltage adjusted to 18 Vac, Rg = 50,000 ohms, Rb = 20,000 ohms.

Other characteristics are as follows:

Group	Type	Ef, V	If, A	Maximum ratings, Triode, Eb, Vdc	Maximum ratings, Triode, Pp, W	Maximum ratings, Heptode, Pp, W	Maximum ratings, Heptode, Pg2 + 4 W	Maximum ratings, Heptode, Ik mAdc	Test conditions, Heptode, Ec1, Vdc	Test conditions, Heptode, Ib, mAdc	Test conditions, Heptode, Ic2 + 4, mAdc	Test conditions, Heptode, Sc, μmhos	Cutoff char. Heptode, Ec1, Vdc	Cutoff char. Heptode, Sc, μmhos, avg	Limits, Ib, mAdc, Min.	Ib, mAdc, Max.	Ic2 + 4, mAdc, Min.	Ic2 + 4, mAdc, Max.	Ik, mAdc, Min.	Ik, mAdc, Max.	Sc, μmhos, Min.	Sc, μmhos, Max.	Emission test, Is, mAdc, min.	Base	Bulb	Notes
1	6J8G	6.3	0.30	165	....	...	...	15.5	−3	1.3	2.9	290	−20	2	0.6	2.0	1.4	5.6	8.0	14.0	200	400	70	Oct, TC	ST-12	
2	7J7	6.3	0.30	165	1.25	...	...	14.5	−3	1.4	2.8	290	−20	2	0.9	2.0	1.1	4.5	7.4	12.1	200	400	80	Loc	T-9	(1), (2)
	14J7	12.6	0.15																					Loc	T-9	(1), (2), (3)
3	7S7	6.3	0.30	175	1.0	0.6	0.4	14.5	−2	1.8	3.0	525	−21	2	1.1	2.6	1.2	4.8	7.4	12.6	340	710	90	Loc	T-9	(1)
	14S7	12.6	0.15																							

For all types the oscillating triode Ic1 = 300 μAdc min; 400 av.; the maximum is 550 μAdc for groups 1 and 3 and 600 for group 2. For the nonoscillating condition Heptode Eb = Ec2 + 4 = Ec1 = 0; the triode characteristics are:

Types	Eb, Vdc	Ec, Vdc	gm, μmhos, Min.	gm, μmhos, Avg	Ib, mAdc, Min.	Ib, mAdc, Avg	Ib, mAdc, Max.	Mu
6J8G	150	−3	1350	1600	6.0	...	12.0	..
7J7, 14J7	150	−3	1150	1400	4.3	6.6	9.3	15
7S7, 14S7	100	0	1350	1650	4.2	6.5	9.1	18

NOTES: (1) Maximum Ic1 = 550 μAdc.
(2) Will operate satisfactorily up to 100 Mc/sec.
(3) Also has ratings for 28-volt operation: Triode Eb = 28 Vdc. Heptode Eb = Ec2 + 4 = 28 Vdc. Triode Ec1 = 0, Rg1 = 50,000 ohms, g1 signal voltage 3.4 Vac. Heptode Ec1 = −0.75 Vdc. Sc = 160 μmhos min, 310 max.

Interelectrode capacitances in $\mu\mu$f

Capacitance	6J8G Min.	6J8G Max.	7J7, 14J7 Min.	7J7, 14J7 Max.	7S7, 14S7 Min.	7S7, 14S7 Max.
Heptode g1 to all others	3.6	6.0	3.7	5.5	3.7	6.3
Heptode p to all others	7.3	12.5	5.5	9.5	6.0	10.0
Heptode g1 to p	...	0.02	...	0.02	...	0.03
Heptode g1 to triode p	...	0.015	...	0.10	...	0.10
Heptode g1 to triode g1	...	0.13	...	0.30	...	0.35
Triode g1 to p	2.2 Avg		0.9 Avg		1.0 Avg	
Triode p to all others	5.5		...	....	...	....
Triode p to all except triode g1	.	.....	3.2 Avg		3.5 Avg	
Triode g1 to all others	11.7		...	.....	...	.....
Triode g1 to all except triode p	...	.....	7.5 Avg		7.0 Avg	

applications. The first grids of all the triode-heptode types of Table 29 have sharper cutoff characteristics and it should be possible to use the heptode sections of these types in similar applications by not using the triode sections. No information is available on such operation of these tubes.

The Radiation Laboratory made comparatively little use of converter tubes. The 6SA7 (27-4) was used as an electron-coupled oscillator-

TABLE 30.—PENTAGRID MIXERS

This class includes only three types, all belonging to one group. The 6L7 and 1612 are metal tubes with an octal base and top cap; the 6L7G has an ST-12 bulb with an octal base and top cap. All have 6.3-volt 0.3-ampere heaters. The 1612 is a 6L7 selected for nonmicrophonic characteristics for use in audio applications; no characteristics are given except maximum ratings as an amplifier, which are the same as for the other types except that Eb = 275 Vdc max. Presumably the other characteristics are identical with those of the other types. For the 1612 Cg3-p = 0.1 $\mu\mu$f max. Other capacitances are:

Type	Cg1—all others, $\mu\mu$f		Cg3—all others, $\mu\mu$f		Cp—all others, $\mu\mu$f		Cg1-p, $\mu\mu$f max.	Cg1-g3, $\mu\mu$f max.
	Min.	Max.	Min.	Max.	Min.	Max.		
6L7	6.2	8.8	8.3	11.7	8.2	13.8	0.001	0.2
6L7G	4.9	7.1	12 Av.		7.2	12.8	0.005	0.2
1612	7.5 Av.		10 Av.		11 Av.		0.001	. . .

The other characteristics are:

Maximum ratings:

As an amplifier, Eb = 330 Vdc, Ec2 + 4 = 110 Vdc, Pp = 1.5W, Pg2 = 1.0 W, Ehk = 100 Vdc.

As a mixer, Eb = 300 Vdc, Ec2 + 4 = 165 Vdc, Pp = 1.0 W, Pg2 = 1.5 W, Ehk = 100 Vdc.

Test conditions:

As an amplifier Eb = 250 Vdc, Ec2 + 4 = 100 Vdc, Ec1 = Ec3 = −3Vdc, Ib = 5.3 mAdc, Ic2 + 4 = 6.5 mAdc, gm = 1100 μ mhos.

As a mixer, Eb = 250 Vdc, Ec2 + 4 = 100 Vdc, Ecl = −3 Vdc, Ib = 2.4 mAdc, Ic2 + 4 = 7.1 mAdc, Ec3 = −10 Vdc, peak signal voltage = 12 v min, Sc = 375 μmhos.

Cutoff characteristics as an amplifier:

For gl, Ec1 = −30 Vdc, gm = 1 μmho min, 20 max.

for g3, Ec3 = −15 Vdc, gm = 1 μmho min, 55 max.

Limits of essential characteristics as an amplifier:

Ib = 3.6 mAdc min, 7.0 max. Ic2 + 4 = 4.7 mAdc min, 8.5 max. gm = 900 μmhos min, 1300 max.

Maximum Ic3 = −2.0 μAdc.

For h-k leakage test, Ihk = 20 μAdc max for Ehk = 100 Vdc.

For emission test, with all grids and the plate at 30 Vdc, Is = 45 mAdc min.

TABLE 31.—COLD-CATHODE GAS DIODES (VOLTAGE REGULATORS)

Group	Type	Ratings				Test conditions and characteristics									Leakage, Eb = 50 Vdc, Ib μAdc max.	Base	Bulb	Notes
		Nominal operating voltage, Vdc	Minimum starting voltage, Vdc	Operating current, mAdc Min.	Operating current, mAdc Max.	Ebb Vdc	(1) Rp/Ib mAdc	(2) Rp/Ib mAdc	(3) Rp/Ib mAdc	Ib = (1) Eb Vdc max.	Ib = (2) Eb Vdc max.	Ib = (3) Eb Vdc max.	Regulation Ib(1) to Ib(3) Vdc max.	Regulation Ib(2) to Ib(3) Vdc max.				
1	0C2(S859)	75	...	5	30	...	..	..	....	...	...	...	...	....	..	Min	T-5½	(1)
2	0A3/VR75	75	105	5	40	150	40	30	5	81	79	70	6.5	4.5	10	Oct	ST-12	(2)
3	0B3/VR90	90	130	5	30	150	..	30	5	...	100	80	...	6.0	10	Oct	ST-12	
4	874	90	130	10	50	300	..	50	10	...	100	80	...	10.0	10	4	ST-16	(2)
5	0B2(HD52)	105	133	5	30	...	..	30	5	...	...	...	...	1.0Av.	...	Min	T-5½	(1)
6	0C3/VR105	105	127	5	40	300	40	30	5	112	111	105	4.0	2.0	10	Oct	ST-12	(2)
7	0A2	150	185	5	30	...	...	30	5	...	...	...	...	2.0Av.	...	Min	T-5½	(2)
8	0D3/VR150	150	180	5	40	300	40	30	5	162	160	145	5.5	4.0	10	Oct	ST-12	(2)
9	991	60	87	0.4	2	...	..	2	0.4	...	67	48	...	8.0	..	Bay	T-4½	(3)
10	1B46	80	225	1	2	250	..	2	1	...	85	79	...	3.0	..	Bay	T-4½	(4)
11	1B47	80	225	1	2	250	..	2	1	...	90	75	...	3.0	..	Bay	T-4½	(4)

NOTES: (1) Types 0C2 (S859) and 0B2 (HD52) are developmental types.
(2) Maximum range of operating temperatures is $-55°$ to $+90°C$.
(3) Type 991 has a nonpolarized base (same as ordinary 2-contact automobile bulb). Specifications apply to tube connected in either direction.
(4) Polarized base.

converter and as a time selector. It is not as good as the 6AS6 for the latter application since its g3 cutoff is not as sharp. It was successfully used in the phantastron circuit, as was also the 7A8 octode (26-3).

14·6. Gas-filled Tubes.—This section presents data on only a small number of the many gas-filled tubes that are available on the market, and on only three classes—cold-cathode diode voltage regulators and hot-cathode triodes and tetrodes of small size and comparatively low power-handling capacity.

Voltage-regulator Diodes.—The characteristics of the cold-cathode gas diodes intended for voltage regulation are given in Table 31.

Three of the types in the table, the 1B46, 1B47, and 991, have low maximum current ratings in comparison with the other types. The 874 is of older design and has a large physical size. These types will not be further discussed.

The remaining types are made with four nominal values of voltage drop, as follows:

0A8/VR75 and (miniature) 0C2	75 volts
0B3/VR90	90 volts
0C3/VR105 and (miniature) 0B2	105 volts
0D3/VR150 and (miniature) 0A2	150 volts

The miniature types appear to be identical in all respects with their larger counterparts, except for a slightly lower maximum current rating. The regulation characteristics of the several types vary considerably, both with regard to the absolute value of voltage change and to the nominal voltage drop. The 105-volt tubes have the best regulation, followed in order by the 150- and the 75-volt types, with the VR90 a poor fourth. The differences are apparently due to the different gas mixtures used, and also perhaps to other causes.

The Radiation Laboratory made extensive use of regulator diodes both directly as voltage regulators and also as standard voltage sources for regulated power supplies.

Gas Triodes and Tetrodes.—Tables 32 and 33, respectively, list small grid-controlled gas triodes and tetrodes (Thyratrons). In addition to those listed in these tables there are many larger types with power-handling capabilities running up to hundreds of kilowatts.

Of the triodes the 884 and 885 (32-3) are the most widely used, the latter type having a somewhat obsolescent heater voltage and base. Two miniature triodes are available, the 6D4 (32-4) and the 2C4 (32-5). These two types have considerably lower current ratings than the larger tubes.

For many applications the tetrodes of Table 33 are preferable to the triodes, since they will operate on smaller input signals and have higher

TABLE 32.—SMALL HOT-CATHODE GAS TRIODES (THYRATRONS)

Group	Type	Ef, V	If, A	Maximum ratings											Starting voltage tests					Tube-drop test			Avg Etd Vdc	Leakage test		Base	Bulb	Notes
				epx, v	epy, v	Ebb, Vdc	e between any two electrodes, v	ib, ma	Ib, mAdc	ig, ma	Ehk, Vdc	tk, sec	Temp. range, °C		Ebb Vdc	Rp ohms	Rg megohms	Ec, Vdc		Ebb Vdc	Rb/Ib mAdc	Etd Vdc max.		Ehk Vdc	Ihk μAdc max.			
													Min.	Max.				Min.	Max.									
1	338A	10.0	0.5	300	300	...	325	600	100	10	±50	60	....	....	250	5000	0.001	−4	−10	250	100	20	..	+100	500	5	ST-12	(1), (2)
2	2A4G	2.5	2.5	200	200	...	250	1250	100	..	xx	2	....	....	75	nn	....	−4	−6	200	100	20	15	xx	xx	Oct	ST-12	(3)
															150	nn	.....	−6.5	−8.5									
3	884	6.3	0.6	300	300	...	350	300	75	1	+25, −100	30	−60	+85	110	1700	0.1	−10	−14	50	300	20	16	100	20	Oct	ST-12	(1), (4)
	885	2.5	1.5																							5	ST-12	
	884	6.3	0.6												250	5600	0.1	−21.0	−29.0							Oct	ST-12	
	885	2.5	1.5																							5	ST-12	
4	6D4	6.3	0.25	350	350	250	...	110	25	..	+25, −110	30	−55	+90	125	650	0.5	−11	−14	...	...	..	16	−100	15	Min	T-5½	(5)
															50	650	0.5	−5.0	−7.0									
5	2C4	2.5	0.6	350	350	250	...	22	5	..	+100	30	....	....	125	2000	0.5	−11.5	−13.5	125	5	17	16	100	15	Min	T-5½	(6)

NOTES: (1) For oscillator service Ib = 2 mAdc max.
(2) Etd = 8 Vdc min.
(3) Oxide-coated filament; all other types in table have heater-type cathodes.
For starting-voltage tests adjust plate resistor so that Ib = 100 mAdc.
(4) Maximum value of Rg is 0.5 megohm. Average interelectrode capacitances are: Cin, 2.0 μμf; Cout, 0.6 μμf; Cgp, 6.0 μμf.
(5) For pulsed operation max. ratings are: Ebb = 350 Vdc, ib = 2000 ma, Ib = 15 mAdc, Ehk = −200 v peak, pulse length = 10 μsec max.
For starting-voltage test Rk = 4000 ohms.
For instantaneous tube-drop test, adjust Rp + Rk so that ib = 2000 ma; etd = 90 v max.
Ec = −150 Vdc max.
(6) For starting-voltage test Rk = 20,000 ohms.

TABLE 33.—SMALL HOT-CATHODE GAS TETRODES (THYRATRONS)

Group	Type	Ef, V	If, A	Maximum ratings, epx, v	epy, v	Ec2, Vdc	Ec1, Vdc	ik, ma	Io mAdc	Rg1 meg-ohms	Ehk, Vdc	tk, sec.	Temp. range, °C. Min.	Temp. range, °C. Max.	Starting-voltage tests, Epp, Vac	Ec2, Vdc	Rg1, meg-ohms	Rp, ohms	Ec1, Vdc Min.	Ec1, Vdc Max.	Tube-drop test, Ebb, Vdc	Rg1, meg-ohms	Rp, ohms	Ec1, Vdc	Ib, mAdc	Etd, Vdc, max.	Avg Etd, Vdc	Leakage test Ehk, Vdc	Leakage test Ihk, μAdc, max.	Base	Bulb	Notes
1	2050	6.3	0.6	1300	650	100	−100	500	100	10	+25 −100	10	−60	+75	460	0	0.1	980	−2.9	−4.5	300	0.1	10000	0	300	11	8	−100	20	Oct	ST-12	(1)
	2D21												−50	+65				3000												Min	T-5½	(2)
	2050												−60	+75	460	0	10	980	0	−7										Oct	ST-12	(1)
	2D21												−50	+65				3000												Min	T-5½	(2)
	GL502A						−200						−60	+75	...	..	.....	....	.....	.....	...	...	....	..	...	..	11	.....	..	Oct	Metal	(3)
2	GL546	6.3	0.15	500	500	...	.....	100	20	10	.....	10	−40	+80	...	..	.....	....	..	.....	...	...	....	..	...	..	15	.....	..	Min	T-5½	(4)

NOTES: (1) Manufacturer's rating gives ik = 1000 ma max. Value in table is from JAN-1A. Average interelectrode capacitances are: Cin, 4.2 μμf; Cout, 3.6 μμf; Cgp, 0.26 μμf. Manufacturer also specifies operating temperature range of −55 to +90°C.

(2) Average interelectrode capacitances are: Cin, 2.4 μμf; Cout, 1.6 μμf; Cgp, 0.20 μμf. Manufacturer specifies operating temperature range of −55 to +90°C.

(3) Manufacturer specifies operating temperature range of −55 to +90°C. Cgp is 0.20 μμf average.

(4) Temperature range as given by manufacturer. Cgp is 0.10 μμf average.

ratings for comparable size and heater power. At one time they were considerably more expensive than the triodes, but this is no longer true.

In Table 33 there are only two basic types, since the 2050 (and its nearly identical twin, the now-obsolete 2051), the miniature 2D21, and the metal GL502A are practically identical except for physical construction. The miniature GL456 has one-fourth the heater power of the others and lower ratings.

All of the types, both triodes and tetrodes, have negative values of critical control-grid voltage, although the tetrodes of group 33-1 can be given a positive grid characteristic by biasing the screen slightly negative.

Thyratrons were used by the Radiation Laboratory for a number of purposes, ranging from oscilloscope sweep generation to the control of fairly large servo motors. The useful characteristics of the tubes of Tables 32 and 33 can be summarized as follows:

884—Argon-filled triode. Safe peak current 1 amp. Useful as switch tube in delay-line pulse generators, as oscilloscope time-base generator, and as frequency divider.

6D4—Miniature version of 884. Also useful with magnet as r-f wideband (10 Mc/sec) noise source.

2050—Xenon-filled tetrode. Very low control electrode capacitance. Firing characteristic nearly independent of plate voltage. Useful to control small d-c motors, as an instantaneous amplitude comparator, and as a switch.

2D21—Miniature version of 2050.

3C45—(Not listed in tables.) Best low- and medium-power switch tube. Deionization time 10 to 20 microseconds. Not a good amplitude comparator as it requires large positive grid drive before conduction takes place.

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